NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-5
Delayed Neutron Data – Review and Evaluation

by

Samson A. Cox

April 1974

ARGONNE NATIONAL LABORATORY,
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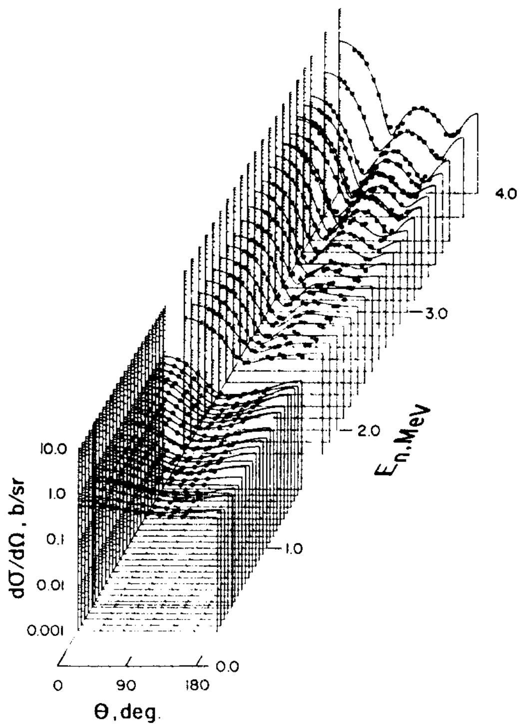

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NUCLEAR DATA AND MEASUREMENTS SERIES

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DELAYED NEUTRON DATA - REVIEW AND EVALUATION

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ABSTRACT

The status of delayed neutron measurements is reviewed. Emphasis is placed on the absolute yield vs. the energy of the neutrons causing fission, group yields and periods, and in the delayed neutron spectra. Systematics are discussed and an evaluated data set, based both on available measurements and on systematics arguments, is suggested for inclusion in ENDF/B-IV. Areas of delayed neutron studies which require additional measurements are outlined.

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9 The available data showing the energy dependence of delayed neutron yield for $E \leq 4$ MeV is presented. All data sets have been normalized to the recommended ENDF/B-IV value. The relative energy dependence is not changed by the normalization but systematic errors which affect only the total yield are eliminated.

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I. INTRODUCTION

A knowledge of the absolute yield, time dependence and spectral characteristics of delayed fission neutron emission is essential to a proper understanding of reactor kinetics. With the advent of fast breeder power plants there is a need for improved precision in delayed neutron data. This involves both measurement and evaluation. The purpose of this report is to review the current status of delayed neutron data relevant to reactor physics and to provide an evaluated data set for use in reactor calculations. Since the motivation is directed toward utilization by reactor physicists, emphasis is placed on absolute total yields including variation of the yield with the energy of the neutrons inducing fission, individual group yields and half lives, and on delayed neutron energy spectra. It is well known that the time dependence of delayed neutron activity can be adequately represented by six precursor groups with approximate half lifes of 55,22,6,2,.5, and .2 seconds[1]. The exact half lives vary with particular nuclides. The six period representation will be followed throughout this report even though the real precursor contribution is much more complex. Tomlinson, for example, lists 45 precursors[2].

A number of reviews and compilations are available which cover most delayed neutron work published through 1971. Of particular value are the Proceedings of a Panel on Delayed Fission neutrons[3], the two symposia on the Physics and Chemistry of Fission[4] and the review and evaluation papers of Tuttle[5], Tomlinson[2], Manero and Konshin[6], and Keepin[7].

II. ABSOLUTE DELAYED NEUTRON YIELDS

Early precision measurements of the absolute delayed neutron yields (neutrons/fission) are concerned with either thermal neutron or "fast neutron" induced fission[1]. The term "fast neutron" is more or less undefined but generally refers to neutrons in the MeV range. It is only recently that detailed measurements of the energy dependence have been reported. The study of Cox and Whiting[8] for Th^{232} and U^{238} extends from below threshold to well into the plateau region. No change in the delayed neutron yield outside experimental error is observed. Similarly their measurements for U^{235} from .2 to 1.5 MeV also indicate a constant delayed neutron yield. The measurements of Krick and Evans[9] in the energy range from .1 to 7 MeV for U^{233}, U^{235}, U^{238}, Pu^{239} and Pu^{242} also indicate a constant delayed neutron yield up to an incident neutron energy of $\sim$ 4 MeV at which point a sharp drop in yield is observed. As a result of the energy dependent studies combined with the earlier thermal and fast neutron data measurements it seems reasonable to conclude that the delayed neutron yield is constant for incident neutron energies less than 4 MeV.

For energies between 4 and 8 MeV, two sets of measurements are reported both of which cover the region of the second chance fission threshold. Krick and Evans[9] report detailed measurements of the total delayed neutron yield up to 6.5 MeV for U^{233}, U^{235} and U^{238}. In each case, the yield shows a sharp drop above 4 MeV to approximately 2/3 of the yield in the region below 4 MeV. A decrease in the yield above the second chance fission threshold is expected since here it is energetically possible for the nucleus formed by the incident neutron to re-emit a neutron with a lower energy and still retain a high fission probability. The fissioning nucleus in this case is one mass unit lighter than the fissioning nucleus below the second chance fission threshold. It is known from delayed neutron systematics that for a given element the delayed neutron yield decreases with decreasing mass number[10]. The amount of the decrease, however, is difficult to understand. As is pointed out by Tuttle[5] the low delayed neutron yield above the second chance threshold implies that the first chance fission cross section has decreased to nearly zero and that almost all of the fission cross section is due to second chance fission. Additional measurements are needed to clarify this point. In addition to the measurements of Krick and Evans[9], Maksyutenko[11] has reported measurements of the relative yield of the first 5 delayed neutron periods in the energy interval from 5 to 8 MeV for Th^{232}, U^{233}, U^{235}, U^{238} and Pu^{239}. In all cases he observes considerable structure associated with the second chance fission threshold. He attributes the structure to changes in the fragment mass yield and fragment charge distribution. Such structure is not observed by Krick and Evans in their total yield measurements. Again additional measurements of the relative group yields combined with a measurement of the total yield are necessary to resolve this point. The area of the most serious disagreement is the region of fission induced by 14-15 MeV neutrons. The measurements fall into two general categories. Pre 1966 measurements (11-15) all of which show an increase over 4 MeV fissions and Post 1966 measurements (16-20) all of which show a decrease from 4 MeV fission. The discrepancy varies from a factor of ~ 2 for U^{235} and U^{238} to a factor of ~ 3 for Th^{232}. It is now generally believed that the measurements which show a decrease in yield are the correct ones although no adequate explanation for such large differences in results has been advanced. The choice of the lower values is supported by the data of Krick and Evans[9] which show an abrupt decrease in yield above $\sim$ 4 MeV to a level which is consistent with the low 14-15 MeV measurements.

One of the arguments used to refute the earlier 14-15 MeV data, which gave high delayed neutron yields, was that the mass and charge distribution should move toward stability with increasing energy and this would result in decreased delayed neutron yields. Such an effect on the delayed neutron yields is not observed in the data of Krick and Evans[9] or in the recent data of Cox[24]. Rather their data show a constant yield up to $\sim$ 4 MeV and an abrupt drop to a value nearly that of the 14-15 MeV data. This indicates that there may be another region between 7-14 MeV of constant yield with presumably another decrease in yield above the third chance fission threshold. Measurements in the 7-14 MeV region would serve to clarify this point. Also precise mass yield data would be of help in understanding the character of the energy dependence of the delayed neutron yield.

On the basis of current information, the energy dependence of the total delayed neutron yield can be constructed from measurements made using thermal or < 4 MeV neutron induced fission and measurements made using 14 MeV neutrons. Systematics data for the total delayed neutron yield (ν_d) is given in Fig. 1 where ν_d values for unmeasured nuclides may be obtained by interpolation. Below the second chance fission threshold ($E_n \sim$ 4-5 MeV) the value of ν_d results from the fission process $A^z + n$ where A is the mass number and z is the atomic number of the bombarded nucleus. Above the second chance fission threshold ν_d corresponds to $(A-1)^z + n$. Above the third chance fission threshold ($E_n \sim 15$ MeV) ν_d corresponds to $(A-2)^z + n$. The location and width of the transition region connecting the low energy first chance fission process to the second chance fission process is inferred from the data of Krick and Evans[9]. Their data is used directly for ^{233}U, ^{235}U, and ^{238}U. For other nuclei, since data does not exist, the region must be estimated. The results of a least squares fit to the Krick and Evans data are given in the following table where E_1 is the neutron energy at the beginning of the transition region and E_2 is the neutron energy at the end.

Nuclide	E_1(MeV)	E_2(MeV)
^{233}U	4.5	6.6
^{235}U	3.9	6.3
^{238}U	4.5	7.2

For ^{232}Th, ^{239}Pu, ^{240}Pu, and ^{241}Pu where data are not available it is recommended that the transition region be represented as the average of the regions for the uranium isotopes. The result is: $E_1 = 4.3$ MeV and $E_2 = 6.7$ MeV. It must be reiterated that this representation has not been verified in detail by experiment but does seem to be suggested by current experimental information.

The data considered in this paper are given in Figs. 2-8 together with the references. The dashed curves represent an idealized form of the energy dependence suggested by the foregoing systematics arguments. No absolute measurements have been made for $E_n > 15$ MeV, thus in the absence of experimental information the dashed curves are terminated at 15 MeV. In the energy range thermal to 15 MeV it is believed that the energy dependence indicated by the dashed curves in Figs. 2-8 represents the best estimate based on currently available information.

The energy dependence for $E_n \leq 4$ MeV is now well established as being essentially constant[8,9,24]. Fig. 9 gives the data of Cox[8,24], and Krick and Evans[9] for ^{233}U, ^{235}U, ^{238}U, and ^{239}Pu. In order to eliminate effects due to a systematic bias in the absolute yield all data in Fig. 9 are normalized to the evaluated yields recommended for ENDF/B-IV (See subsequent section of this report). The evaluated yields are shown by the solid lines. The relative energy dependence of the data is not altered by the renormalization. Error bars of ±5% have been assigned to the data points to aid in demonstrating the degree to which the delayed neutron yield is constant. The 5% figure is not entirely arbitrary. Relative measurements do not contain all of the uncertainties associated with an absolute measurement. Since Krick and Evans[9] assign an uncertainty of 8% to their absolute measurements and Cox[24] assigns an uncertainty of 6% to his absolute measurements an assigned uncertainty of ∿5% to the relative yield seems reasonable. It is evident from Fig. 9 that within the experimental uncertainties the energy dependence is constant for $E_n \leq 4$ MeV. The data of Krick and Evans given in Fig. 9 is represented in Figs. 2-8 as a single point average over their energy interval .1-1.8 MeV. This is done partly for clarity of graphical presentation but also because if systematic biases due to factors related to the particular experimental techniques are to be properly taken into account the weighting factor must apply to the entire set of points from an experimental set up and not to each individual point. For example, if there is a bias due to the energy dependent detection efficiency of the delayed neutron detectors, this bias applies equally to all measurements made with that particular detector arrangement.

One of the factors which prompted the recent measurements of Cox[24] and this paper is the serious discrepancy in the reported values for the absolute delayed neutron yield of $^{238}U + n$ for $E_n \leq 4$ MeV. The degree of agreement or disagreement between various measurements and those of Keepin et al.[1] is shown in Fig. 10. The data are plotted for ^{232}Th, ^{233}U, ^{235}U, ^{238}U, and ^{239}Pu as ratios of the reported yield to that reported by Keepin et al[1]. It is evident that the agreement is rather good for ^{233}U, ^{235}U, and ^{239}Pu. Only for ^{232}Th and ^{238}U is there serious disagreement. Even the data of Masters[17], Clifford[27], and Rose and Smith[26], which is in very poor agreement with the data of Cox[24] and Keepin for ^{238}U, is in good agreement for ^{233}U, ^{235}U, and ^{239}Pu. No explanation for the situation exhibited in Fig. 10 is advanced. The figure is included to emphasize that a problem does exist. It should be pointed out that the relative yields of ^{235}U and ^{238}U as reported by Cox[24] may have a higher degree of reliability than other measurements since the mass determinations of both the ^{235}U and ^{238}U fission foils are made with identical ^{234}U "spiking" and α counting techniques, thus the mass determinations of the ^{235}U and ^{238}U are based on the α-activity of ^{234}U with very minor corrections due to the α - activity of ^{235}U or ^{238}U.

III. GROUP YIELDS AND HALF LIVES

In 1957 Keepin et al.[1] reported the first extensive series of measurements of the delayed neutron group yields and half lives for a large number of nuclides including isotopes of thorium, uranium, and plutonium. Measurements were made with "thermal" neutrons and "fission spectrum" neutron induced fission. In their investigation Keepin et al.[1] tried fitting their data with various numbers of exponential components using the expression:

$$\nu_d = \sum_{1}^{N} A_i e^{-\lambda_i t}$$

They concluded that no significant improvement was achieved by including more than six components (N=6). All their data could be well represented by six components with approximate half lives of 55., 22., 6., 2., .5, and .2 seconds. The exact values depend on the particular nuclide. It is now known[2] that at least 45 precursors contribute to delayed neutron emission. However as a practical matter it is customary to use the six component representation. It should be mentioned that, since the half lives and group yields derived from the data may depend on the particular exponential decomposition method used, both the half lives and group yields must be given to uniquely define a given measurement. It is not proper to use one authors half lives and another authors group yields. <u>The reported half lives and group yields must be treated as a self contained set</u>. The half lives change only slightly from nuclide to nuclide but the relative group yields change by large factors. For example the relative (or fractional) yield of the 55 sec. group changes from .086 for ^{233}U to .013 for ^{238}U.

It is pointed out in the previous section that the total delayed neutron yield is essentially constant for $E_n < 4$ MeV. It is natural to inquire if the group yields and half lives are also independent of neutron energy in this energy interval. The extent to which this is true is now examined. In comparing the results of various authors it is desirable to choose a representation which includes as few subjective biases as possible. Direct comparison of the group half lives and yields tends to reflect the particular features of the decomposition method used by each author in extracting the exponential components from the gross decay curve. Whatever method is used to generate the group yields and half lives the original gross decay curve can be reconstructed by inserting the reported values for the yields and half lives (or decay constants) in the exponential sum:

$$Y(t) = \sum_{1}^{N} A_i e^{-\lambda_i t}$$

The various data can then be compared relative to a standard decay curve. For the standard decay curve $Y_s(t)$ we choose Keepin's fast fission spectrum set[1]. Thus the ratio R(t) is formed for each decay curve measured for a given nuclide:

$$R(t) = Y(t)/Y_s(t)$$

where Y(t) is the gross decay curve reconstructed from a particular author's exponential parameters and $Y_s(t)$ is the gross decay curve measured by Keepin[1] for the nuclide in question. Comparison of the data of various authors in this way should be less subjective than comparison of the individual parameters. This is especially true if the authors do not decompose the decay curve into the same number of exponential components, as is often the case. The ratio data are given in Figures 11, 12, and 13. Fig. 11 shows the results of Cox and Whiting[8] and Maksyutenko[28] for ^{232}Th, ^{235}U, ^{238}U for incident neutron energies <4 MeV. Since the ratios are calculated relative to the fast fission spectrum data of Keepin[1], Keepin's thermal results for ^{235}U are included. It is evident that the data of Cox and Whiting[8] agree well with Keepin over the range of decay times .1-100. sec. The only exceptions are the two measurements for ^{235}U at 1.2 and 1.5 MeV for t > 20 sec. Deviations for long decay times where the intensity of the delayed neutron activity is low can be explained by small uncertainties in background subtraction. The time dependence indicated by the data of Maksyutenko[28] is quite different from that of Cox[8] and Keepin[1]. Even for decay times in the vicinity of 1-2 sec. where background correction is not a problem Maksyutenko's data differs by as much as $\sim$10% for ^{235}U and $\sim$15% for ^{238}U. A possible explanation for the difference is that the reported values for the relative abundances and decay constants are the result of data averaging done in a way such that they are not representative of the original gross decay curve measurement. The data of Cox and Whiting[8] suggest that the time dependence of the delayed neutron decay is energy independent at least up to $\sim$2 MeV. Maksyutenko's data is in agreement with energy independence for ^{232}Th but not for ^{235}U and ^{238}U. For ^{235}U however it is Maksyutenko's thermal measurement which differs most from the data of Keepin. In the absence of additional information it seems reasonable to assume energy independence for the group yields and decay constants for $E_n \leq 4$ MeV which is the region of energy independence of the total yield.

Above 4 MeV the situation is very complex and somewhat confusing. The only group yield measurements available between 4 and 14 MeV are those of Maksyutenko who reported data from 5-8 MeV[28]. The nuclides investigated are ^{232}Th, ^{233}U, ^{235}U, ^{238}U, and ^{239}Pu. A very complicated energy dependence is observed for all of the nuclides studied. Results for ^{232}Th, ^{235}U, and ^{238}U are given in Figs. 11 and 12. The ratios for ^{232}Th and ^{235}U and all but the 7.2 and 7.5 MeV data for ^{238}U are qualitatively what would be expected assuming that the delayed neutron yield in the 5-8 MeV region is from the second chance process. If the fission process above the second chance fission threshold is dominated by the second chance fission process then, using ^{238}U as an example, the ratios in the 5-8 MeV region should agree with the ratio of the delayed neutron yield from the neutron induced fission of ^{237}U and ^{238}U. Since measurement of the neutron induced fission of ^{237}U is not feasible a qualitative estimate may be obtained by forming the ratio of the delayed neutron yield from neutron induced fission of ^{235}U and ^{238}U. If it is further assumed (without any justification) that the ratio appropriate to ^{237}U and ^{238}U can be obtained by linear interpolation the time dependence of the data for 5 MeV $\leq$ E $\leq$ 7.1 MeV is qualitatively reproduced. This qualitative exercise is included only to indicate that the ratios in the 5-8 MeV region are of about the right shape, magnitude and sense to be consistent with the view that the fission process in the 5-8 MeV region is dominated by second chance fission. The complicated energy dependence indicated by the large spread in the ratios is difficult to understand. Maksyutenko[28] suggests that it might be the result of competition between first and second chance fission. Even if this is the case it is still very difficult to explain the strong resonance present in the ^{238}U data at 7.2 and 7.5 MeV. It would be interesting to examine the fission product yields in this energy region. It must be mentioned that the energy dependent structure observed in the group yields by Maksyutenko[28] is not present in the total yield measurements of Krick and Evans[9] who have data up to 6.9 MeV for ^{238}U.

In the vicinity of 14-15 MeV there are a number of measurements available. East et al.[21] report data at 14.7 MeV for ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, and ^{242}Pu. Maksyutenko[28] reports data at 15. MeV for ^{232}Th, ^{235}U, and ^{238}U. Data are reported by Notea[19], Benedict et al.[20], and Brown et al.[22] at 14. MeV for ^{232}Th and ^{238}U. Data are also reported by Bucko[13] at 14.7 MeV for ^{238}U. All of the reported data for ^{233}U,

^{235}U, ^{238}U, and ^{239}Pu are given in Figs. 12 and 13. There is considerable desparity in the data for ^{238}U. The data of East et al.[21] and Maksyutenko[28] are in reasonably good agreement for ^{235}U but the agreement is less good for ^{238}U. An interesting observation can be made concerning the results of East et al.[21] who has data for all of the nuclides in Fig. 13. His data for ^{235}U and ^{238}U yield a ratio $\sim$ unity, at least up to $\sim$50 sec. decay time, indicating a time dependence nearly the same as for Keepin's[1] fast fission spectrum measurements. However for ^{233}U and ^{239}Pu the data of East et al.[21] show substantial deviation from a unity ratio and of the same sense and approximately the same magnitude for both nuclides.

Fig. 14 gives the results of Maksyutenko[28] for incident neutron energies in the vicinity of 20 MeV. Again a very complicated energy dependent structure is evident.

It is evident that further measurements should be undertaken to clear up the situation especially for $E_n > 4$ MeV. If the results of Maksyutenko are confirmed it might have some interesting consequences for the theory of the fission process.

IV. DELAYED FISSION NEUTRON ENERGY SPECTRA

Following the prescription set forth in the introduction it is assumed that the time dependence of the delayed neutron yield can be represented adequately by six precursor groups. The associated half lives for groups 1 through 6 respectively are approximately 55., 22., 6., 2., 0.5, 0.2 sec. The exact value depends on the specific nuclear species.

The history of delayed neutron energy measurements exhibits three short periods of activity separated by long periods of inactivity. In the earliest period (1946-1948) the average energies of the first five delayed neutron groups from thermal fission of ^{235}U were determined. Burgy et al.[29], used a cloud chamber and Hughes et al.[30], used a moderated counter with variable energy dependence. In addition to the average energy determinations, Burgy et al. obtained some information on the spectral shape. In the next period (1955-1956) there were two investigations reported. Bonner et al.[31], used a cloud chamber to study the delayed neutron spectra from thermal fission of ^{235}U. These workers obtained spectra for the first five groups but the statistical accuracy was poor. The first definitive measurements of delayed neutron energy spectra were made by Batchelor and Hyder[32] for ^{235}U. They used a good resolution ($\sim$5%) ^{3}He proportional counter to study the first four neutron groups. Measurements were made with various irradiation and counting times to enhance the yield of particular groups. The measurements covered the energy interval from 100. to 1200 keV and were the first to show definite structure in the energy spectra. All of the measurements mentioned so far dealt only with the thermal fission of ^{235}U. Until quite recently (1969 to present) no spectral data were available for fast neutron induced fission or for the thermal neutron induced fission of other nuclides. In the last few years (i.e., since 1969) a number of investigations have been undertaken. These can be divided into two areas. In the one area the gross delayed neutron spectra were studied primarily to gain information applicable to reactor kinetics. In the other area on line mass separators were used so that the delayed neutron spectra of specific precursors could be studied. The latter area of study is the most useful for nuclear structure studies. Gross delayed neutron spectrum measurements were reported recently by Shalev and Cuttler[33], and by Fieg[34]. Shalev and Cuttler used a ^{3}He proportional counter which had exceptionally good resolution ($\sim$2.5%) to measure the delayed neutron spectra from neutron induced fission of ^{232}Th,

^{233}U, ^{235}U, ^{238} and ^{239}Pu. The samples were irradiated in the Israel Research Reactor-1 and counting and irradiation times were varied to enhance the yields of groups 2 and 4. Their spectra exhibited considerable line structure. Detailed results were given for group 2 neutrons. Results were also given for group 1. No explicit results were given for the other 4 delayed neutron groups. Fieg(34) reported measurements of delayed neutron spectra from 14. MeV neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu, and from thermal neutron induced fission of ^{235}U. While his hydrogen recoil proportional counter did not have as good resolution as the ^{3}He counter of Shalev and Cuttler(33) his measurements extended to lower neutron energies (∿80 keV as compared with ∿150 keV for Shalev and Cuttler). Spectra for the first 4 groups from ^{235}U fission were in good agreement with the results of Batchelor and Hyder(32). At the present time Fieg's(34) data represent the most complete set and in the interest of internal consistency, it is recommended that Fieg's data be used alone for groups 1,3,4 and 5. Where data for groups 5 and 6 do not exist, group 4 can be substituted for 5 and 6 probably without introducing any large error. For group 2 the data of Shalev and Cuttler(33) are probably to be preferred. Their measurements were made in a reactor spectrum which represents a more appropriate neutron energy region than the 14 MeV Fieg(34) data. Comparison of the thermal neutron and 14 MeV neutron data of Fieg(34) for ^{235}U, however, indicates close similarity, so it seems reasonable to apply the 14 MeV spectra data to the low MeV region as well.

A number of measurements of delayed neutron spectra from separated fission products have been reported. Of particular interest are those relevant to groups 1 and 2 (55 sec. and 22 sec.). Group 1 delayed neutrons derive almost entirely from one precursor: ^{87}Br.(3) Group 2 delayed neutrons result almost entirely (96%) from a combination of two precursors:

^{88}Br and ^{137}I.[3] High resolution measurements with good statistical accuracy have been reported by Shalev and Rudstam[35] for ^{137}I. Their measurements extend from ~100 keV to 1500 keV and exhibit well resolved line structure. Shalev and Rudstam[35] point out that the unusually low level density observed in the delayed neutron spectrum from ^{137}I is probably peculiar to ^{137}I and should not be expected in the spectrum from other precursors. Chrysochoides et al.[36], have measured the delayed neutron spectra from the precursors ^{87}Br and ^{88}Br by fast time of flight. They also reported prominent line structure; however, their measurements only extend from 80 to 250 keV and as is clear from the measurements of Shalev et al.[33], Fieg[34], and Batchelor and Hyder[32] the energy spectra extend to well over 1000 keV.

The status of delayed neutron spectrum data can be summed up as follows:

<u>Group 1 (~55 sec)</u>

This group is due almost entirely to one precursor, ^{87}Br and thus should have the same shape for all nuclides. The data of Fieg[34], and Batchelor and Hyder[32] appear to be the best available.

<u>Group 2 (~22 sec)</u>

This group is due almost entirely to two precursors, ^{88}Br and ^{137}I. The data of Shalev and Cuttler[33] which gives explicit results for ^{232}Th, ^{233}U, ^{235}U, ^{238}U and ^{239}Pu appear to be the best set.

<u>Group 3 (~6 sec) and Group 4 (~22 sec)</u>

The set of precursors for these groups is very complex. For ^{235}U the data of Fieg[34] and Batchelor and Hyder[32] are recommended. For ^{238}U and ^{239}Pu the data of Fieg are the only data available.

Group 5 (∿0.5 sec) and Group 6 (∿0.2 sec)

No data is available for these two groups with the exception of ^{238}U. In the absence of other information it is recommended that the spectra for group 4 be used for 5 and 6. The justification for this is that the main precursors are in the same regions of the periodic table and the average energy determined for group 5 is nearly the same as for group 4 so that the overall spectrum should not be greatly different. The spectral data of Fieg(34) and of Shalev and Cuttler(33) are given in Figs. 14-18 and in Tables XIV-XVIII.

V. DATA RECOMMENDED FOR ENDF/B-IV

In the previous sections of this report the delayed neutron yield was evaluated over the neutron energy range thermal $\leq E_n \leq$ 15. MeV. Within this energy range it is believed that the dashed curves given in Figs. 2-8 represent the best current estimate based on available systematics information. The curves are terminated at 14.0-15.0 MeV because there is no information on absolute yield at higher energies. Since one of the requirements of ENDF/B-IV is that the neutron energy range be extended to 20.0 MeV a modified approach must be taken in evaluating the yield at high neutron energy (E_n > 7.0 MeV). The only experimental data for E_n > 7.0 MeV are the measurements between 14.0-15.0 MeV. If the systematics arguments of the previous sections are correct the absolute yield from 7.0-14.0 MeV should be nearly constant at a level somewhat higher than the yield between 14.0-15.0 MeV. Above 15.0 MeV the yield should be lower than the yield between 14.0-15.0 MeV. Since there is no direct experimental information in the regions immediately below or above the 14.0-15.0 MeV region the following method is adopted. The data of Krick and Evans in the 4.0-7.0 MeV region is extrapolated down to a level corresponding to the average yield indicated by the 14.0-15.0 MeV data. The yield is then considered constant from this point up to 20.0 MeV. This represents an approximation, at best, but in the absence of experimental information it is the best that can be done at present. The available systematics suggest that it is a reasonable approximation. Tables I-VI give the data considered in the evaluation.

The evaluated curves (solid line) together with the data are given in Figs. 2-8.

The Krick and Evans data plotted in the figures for ^{233}U and ^{235}U are the data as reported in Ref. 9. Since Krick and Evans did not supply absolute yields for their ^{238}U data their data in the transition region has been normalized to the evaluated yield for $E_n \leq 4$ MeV.

The data recommended for ENDF/B-IV are given in Tables VII to XIII. The relevant delayed neutron group spectra from Fieg[34] and Shalev and Cuttler[33] are given in Tables XIV to XVIII.

VI. NEED FOR ADDITIONAL MEASUREMENTS

For $E_n \leq 4$ MeV the total yield data for ^{233}U, ^{235}U, and ^{239}Pu seem to be in good shape. There remains an unexplained discrepancy in the total yield data for ^{238}U. The data of Cox[24] and Keepin[1] agree within $\sim$3%, and the data of Clifford[27] and Masters[17] agree within $\sim$3%, however the centroid of the two sets differ by $\sim$12%. Whether additional measurements would help resolve the problem or add to the confusion is a matter for conjecture. A region where additional measurements are definitely needed is for $E_n > 4$ MeV. At the present time the only absolute yield data available are the total yield data of Krick and Evans[9] for ^{233}U and ^{235}U from 4.-7. MeV (group yields and periods were not measured), and measurements in the vicinity of $E_n \sim 15.$ MeV. There is a need for data between 4. and

20. MeV to firmly establish the energy dependence. The present evaluation must depend heavily on systematics arguments to fill in the gaps. While there is considerable justification for the systematics arguments used it is still an unsatisfactory situation when, for most of the nuclides of interest, there is no data available from 4. to 20. MeV except in the vicinity of 15 MeV. In fact for ^{240}Pu and ^{241}Pu there are 3 data points for each, one at low energy ($\sim$2 MeV for ^{240}Pu; thermal for ^{241}Pu) and 2 between 14 and 15 MeV. The suggested energy dependence must rely almost entirely on systematics arguments.

In addition to the absolute total yield measurements suggested above there should be careful measurements of the group yields and periods in the region for $E_n > 4$ MeV. The data of Maksyutenko[28] indicates strong structure in the energy dependent yields in the region from 5-8 MeV and from 18-21 MeV. Such structure, if confirmed, could have very important implications for the theory of the fission process.

There also remains the as yet unexplained rise in ν_d when the incident neutron energy is raised from thermal energy to $\sim$1 MeV. Keepin's data gives a rise of $\sim$5% for ^{235}U and ^{239}Pu, and $\sim$10% for ^{233}U.

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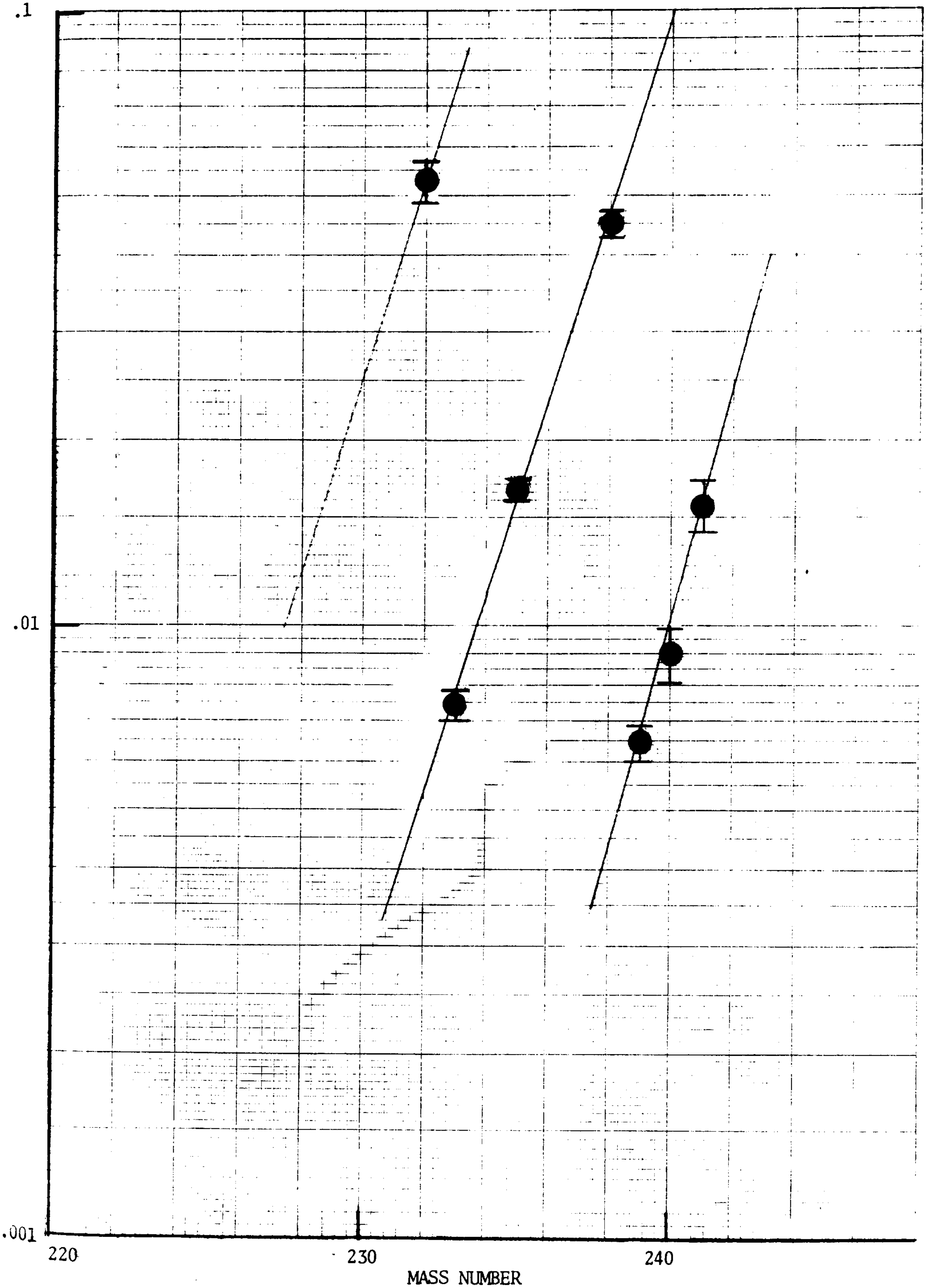
Fig. 1



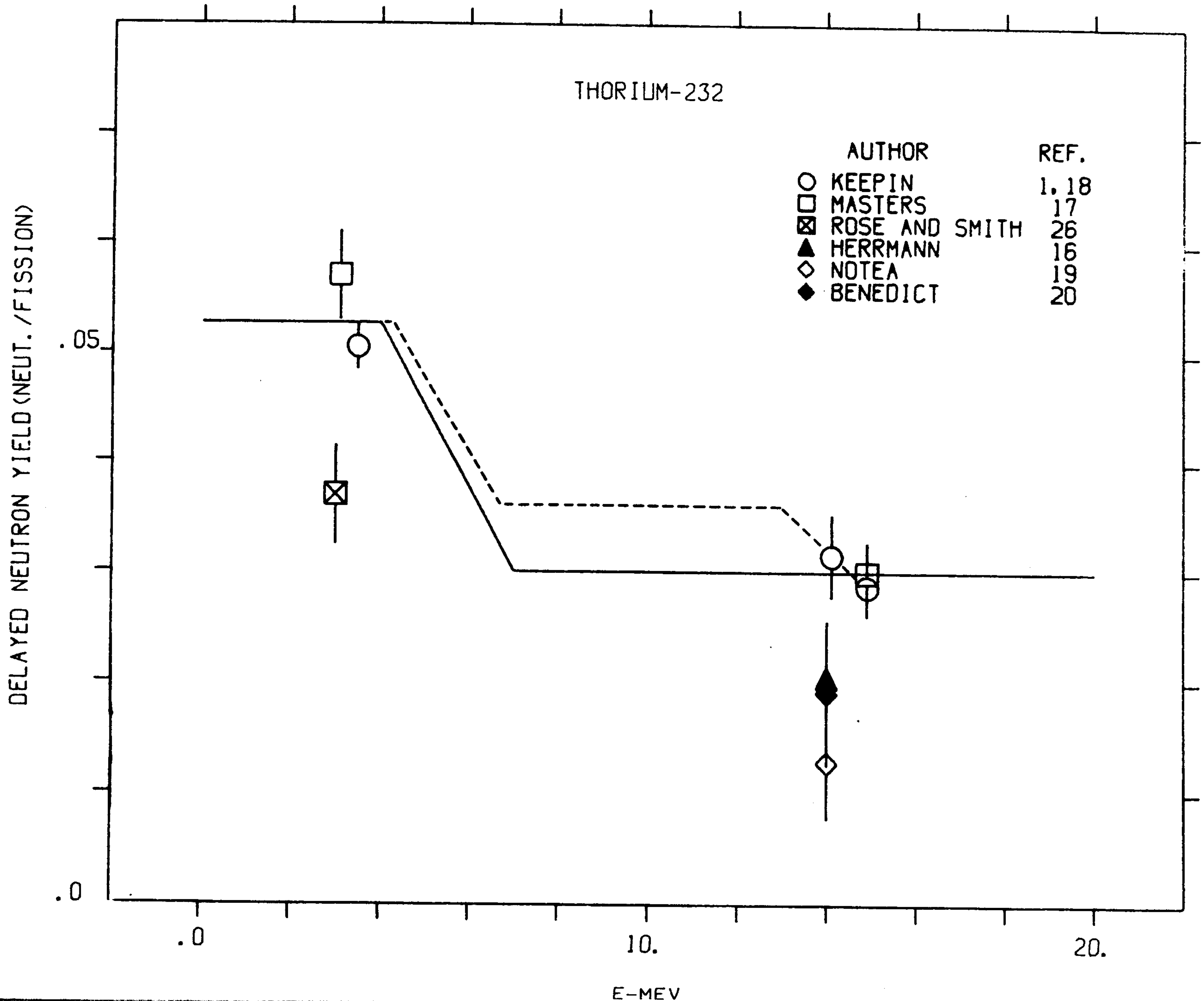

THORIUM-232
AUTHOR REF.
KEEPIN 1, 18
MASTERS 17
ROSE AND SMITH 26
HERRMANN 16
NOTEA 19
BENEDICT 20
DELAYED NEUTRON YIELD (NEUT./FISSION)
.05
.0
.0
10.
20.
E-MEV

Fig. 2

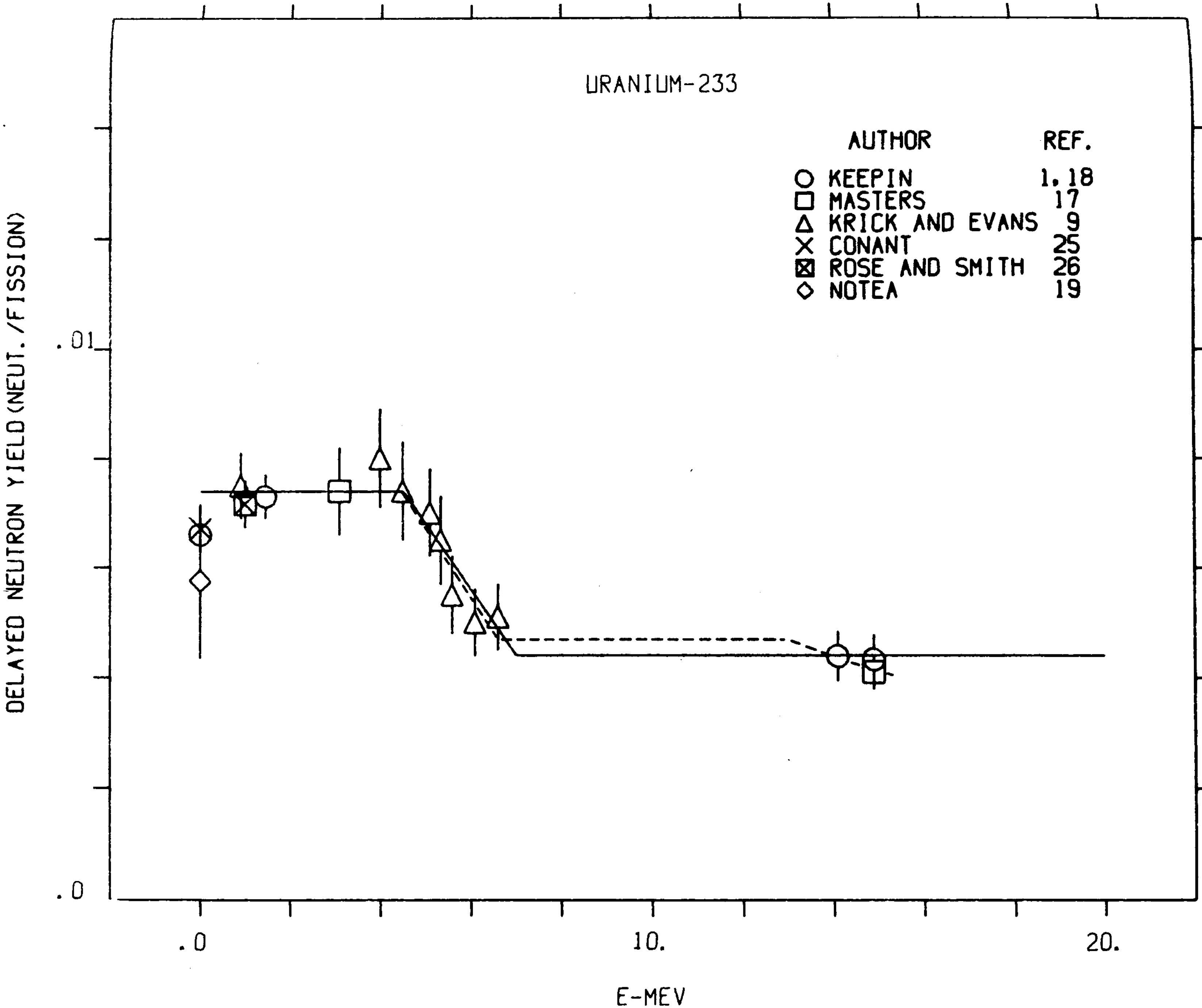

URANIUM-233
AUTHOR REF.
KEEPIN 1,18
MASTERS 17
KRICK AND EVANS 9
CONANT 25
ROSE AND SMITH 26
NOTEA 19
DELAYED NEUTRON YIELD(NEUT./FISSION)
.01
.0
.0
10.
20.
E-MEV

Fig. 3

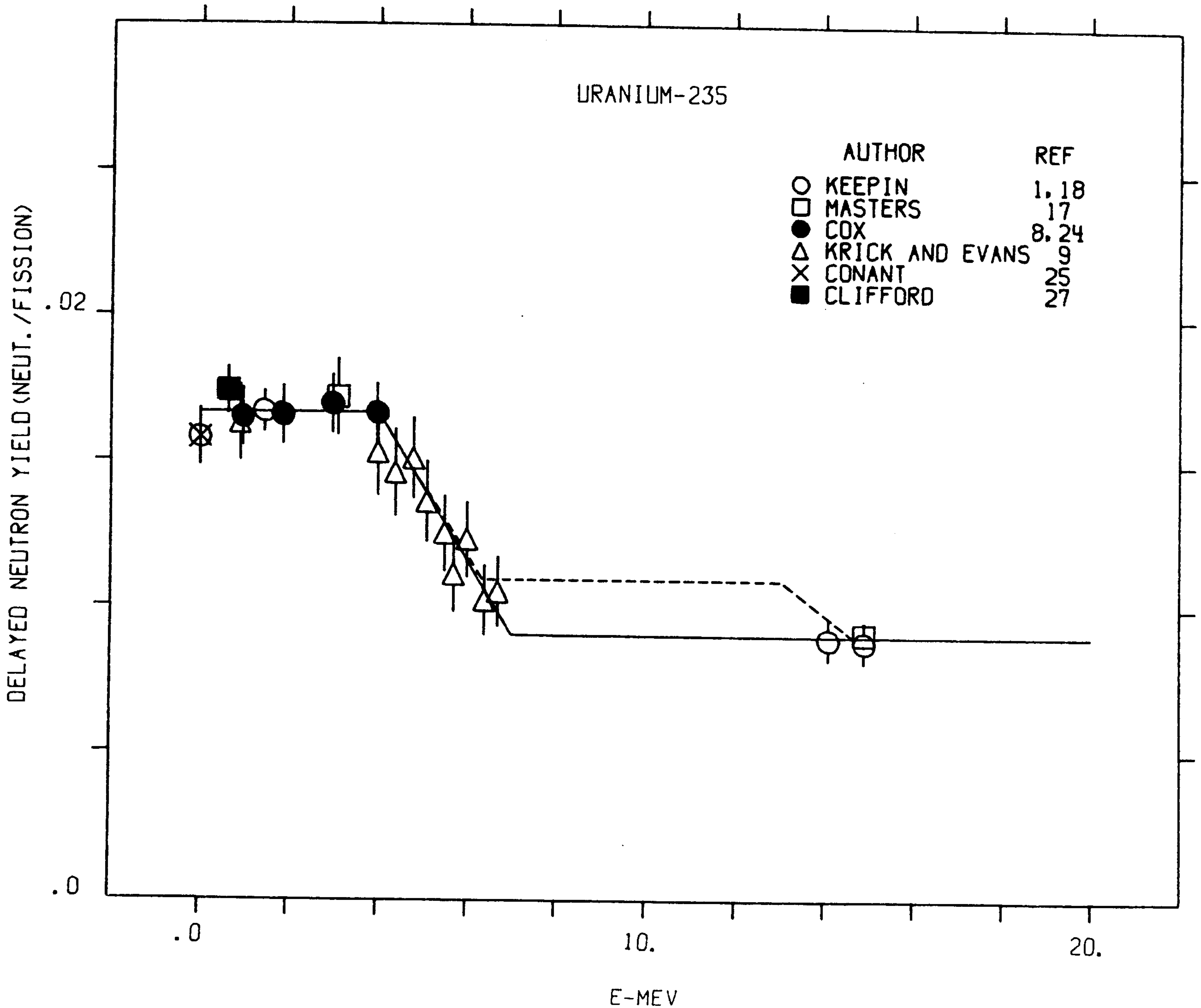

URANIUM-235
AUTHOR
REF
KEEPIN
1, 18
MASTERS
17
COX
8, 24
KRICK AND EVANS
9
CONANT
25
CLIFFORD
27
DELAYED NEUTRON YIELD (NEUT./FISSION)
.02
.0
.0
10.
20.
E-MEV

Fig. 4

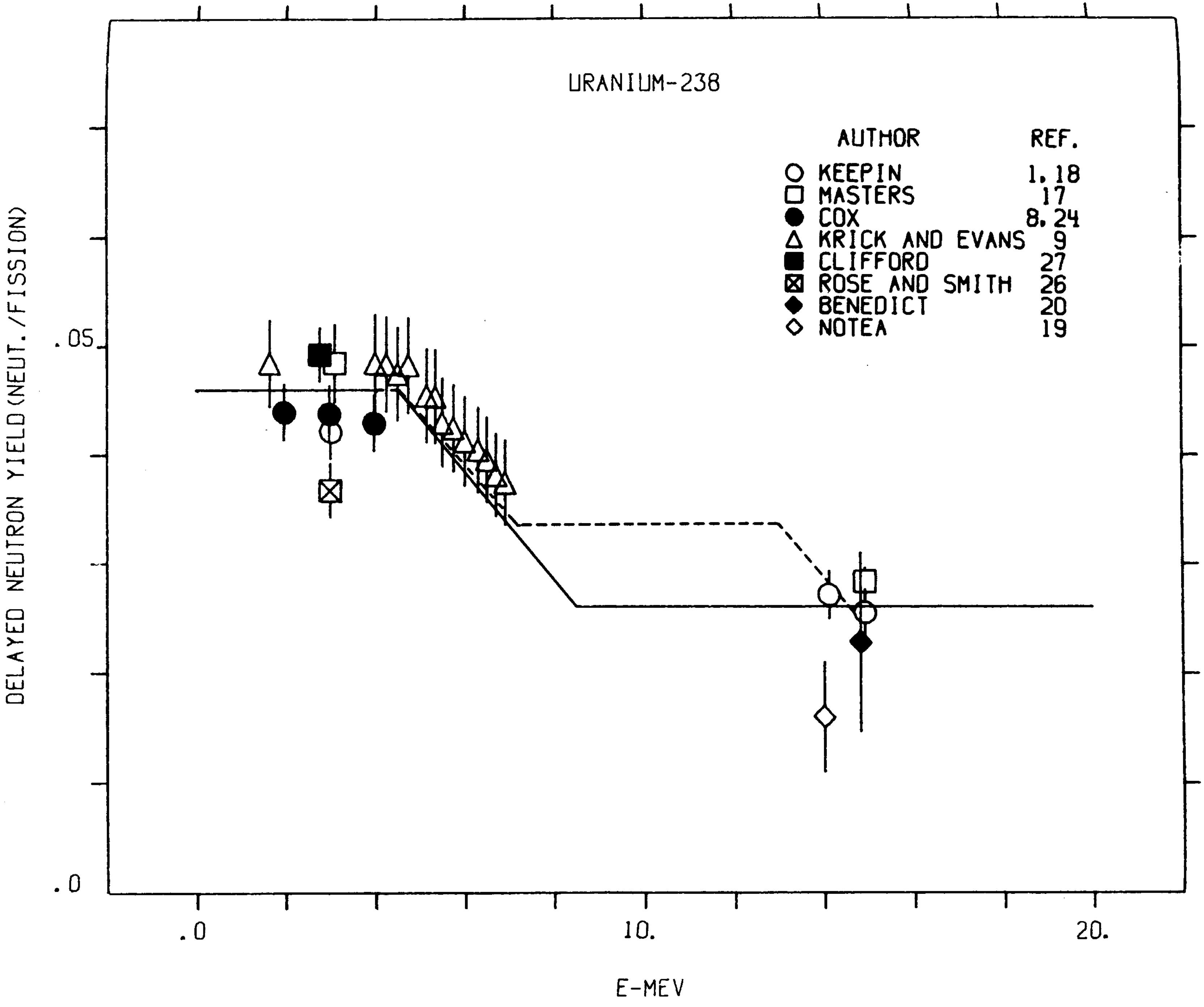
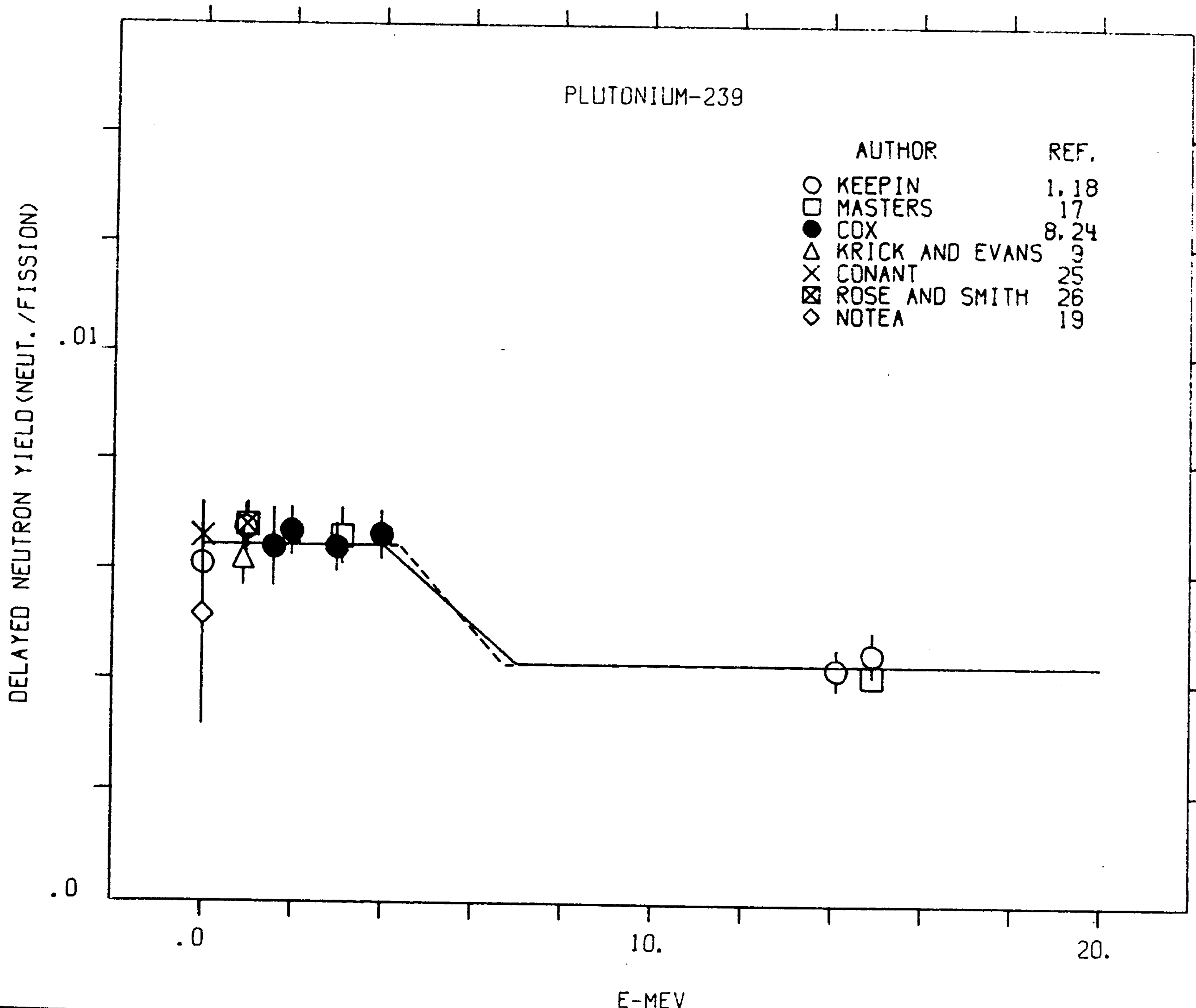
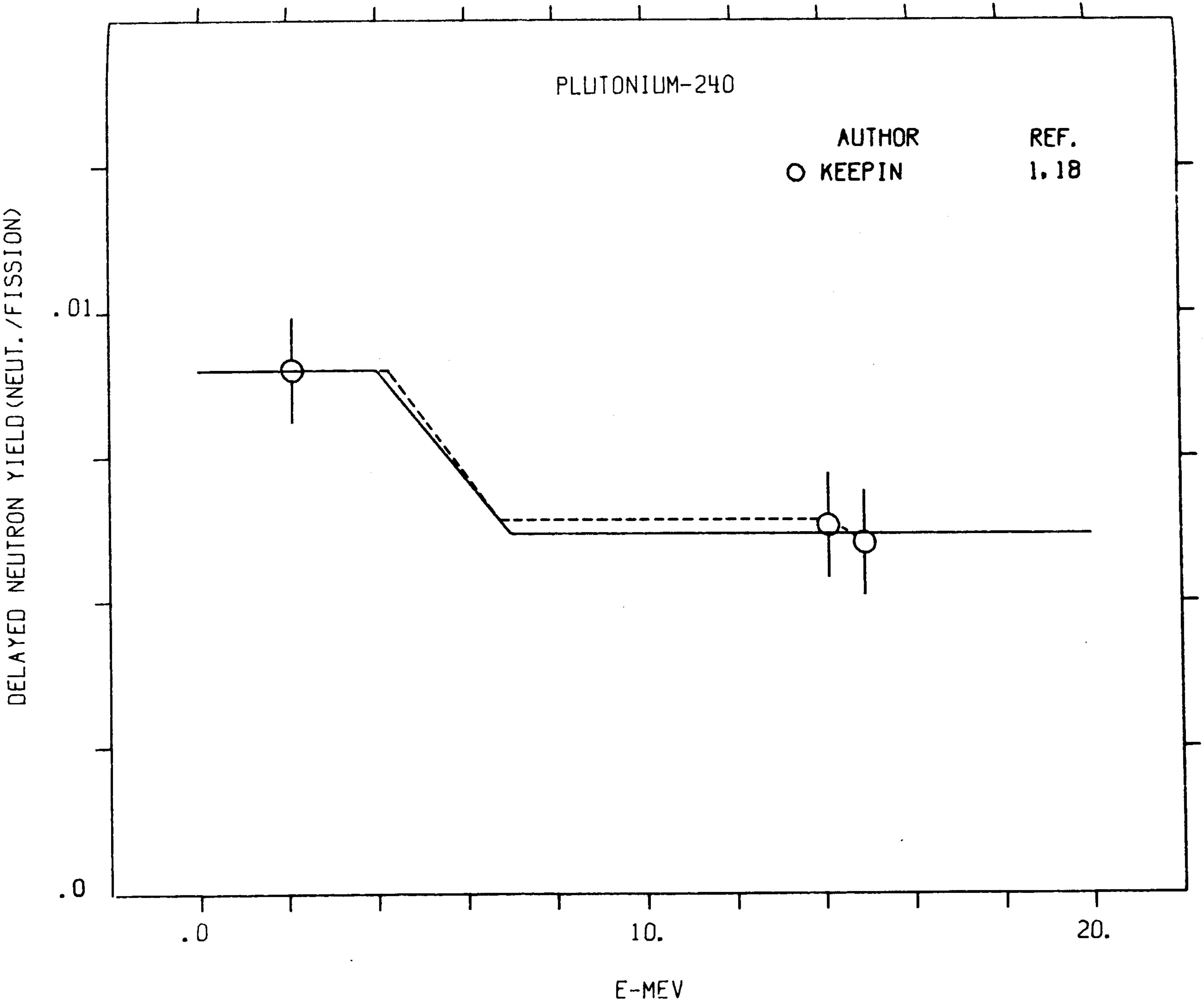

URANIUM-238
AUTHOR REF.
KEEPIN 1, 18
MASTERS 17
COX 8, 24
KRICK AND EVANS 9
CLIFFORD 27
ROSE AND SMITH 26
BENEDICT 20
NOTEA 19
DELAYED NEUTRON YIELD (NEUT./FISSION)
.05
.0
.0
10.
20.
E-MEV

Fig. 5



PLUTONIUM-239
AUTHOR REF.
KEEPIN 1,18
MASTERS 17
COX 8,24
KRICK AND EVANS 9
CONANT 25
ROSE AND SMITH 26
NOTEA 19
DELAYED NEUTRON YIELD(NEUT./FISSION)
.01
.0
.0
10.
20.
E-MEV

Fig. 6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AUTHOR
REF.
KEEPIN
1.18
DELAYED NEUTRON YIELD(NEUT./FISSION)
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.0
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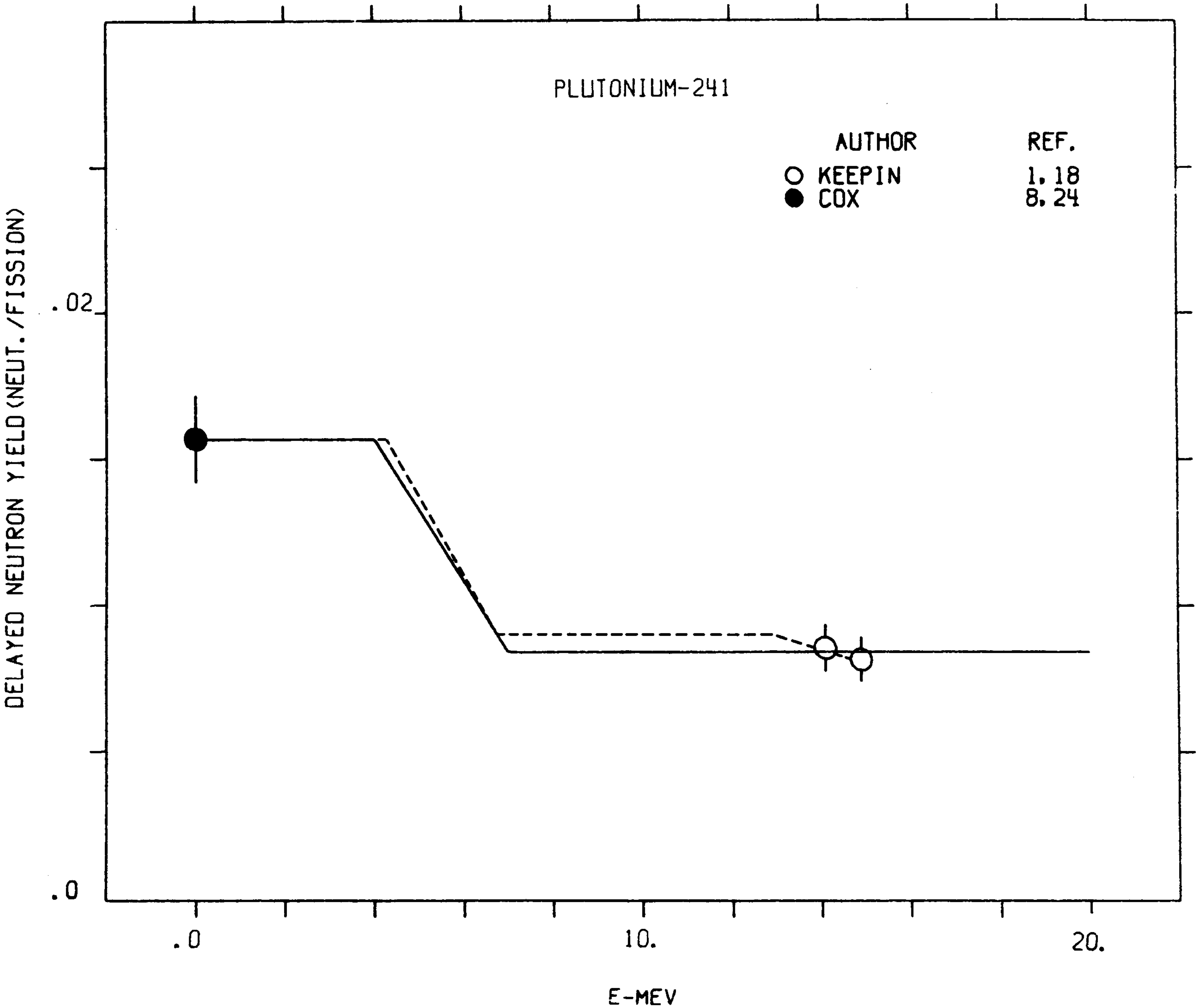
10.
20.
E-MEV

Fig. 7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AUTHOR
REF.
KEEPIN
1.18
COX
8.24
DELAYED NEUTRON YIELD(NEUT./FISSION)
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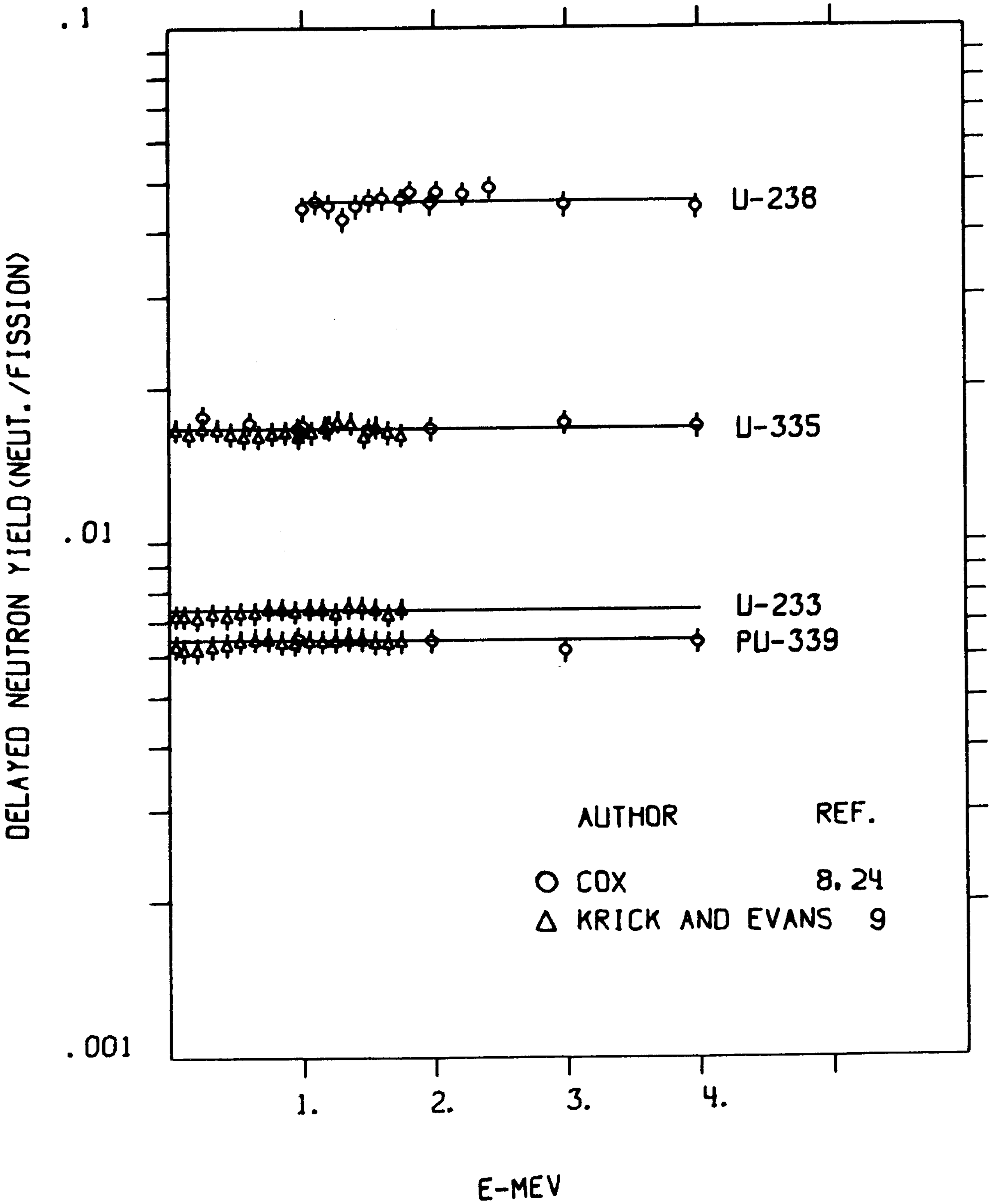
.0
.0
10.
20.
E-MEV

Fig. 8

Fig. 9



.1
.01
.001
DELAYED NEUTRON YIELD (NEUT./FISSION)
U-238
U-335
U-233
PU-339
AUTHOR
REF.
○ COX
8, 24
△ KRICK AND EVANS
9
1.
2.
3.
4.
E-MEV

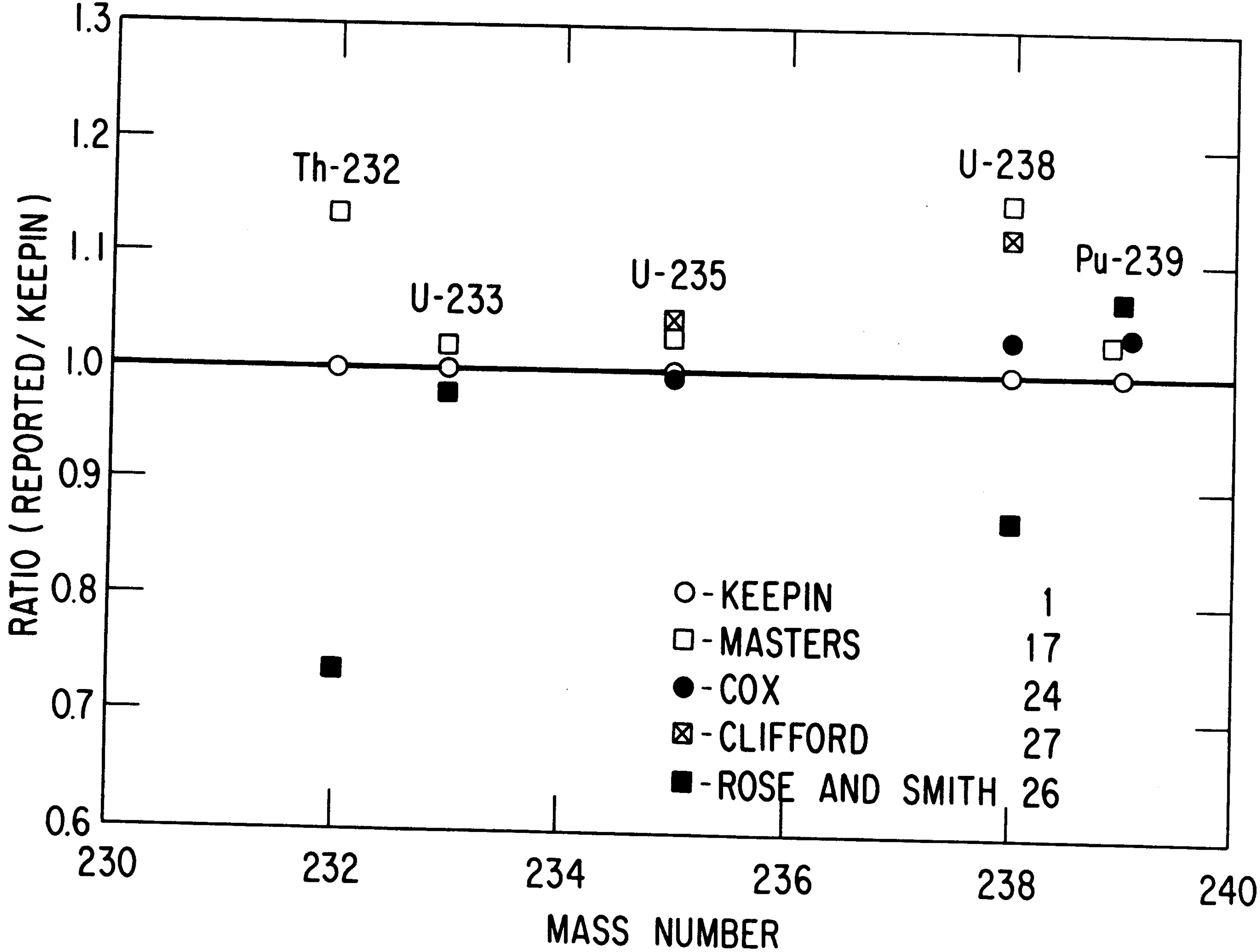

1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
RATIO (REPORTED/KEEPIN)
Th-232
U-233
U-235
U-238
Pu-239
○ - KEEPIN 1
□ - MASTERS 17
● - COX 24
⊠ - CLIFFORD 27
■ - ROSE AND SMITH 26
230
232
234
236
238
240
MASS NUMBER

Fig. 10

Fig. 11

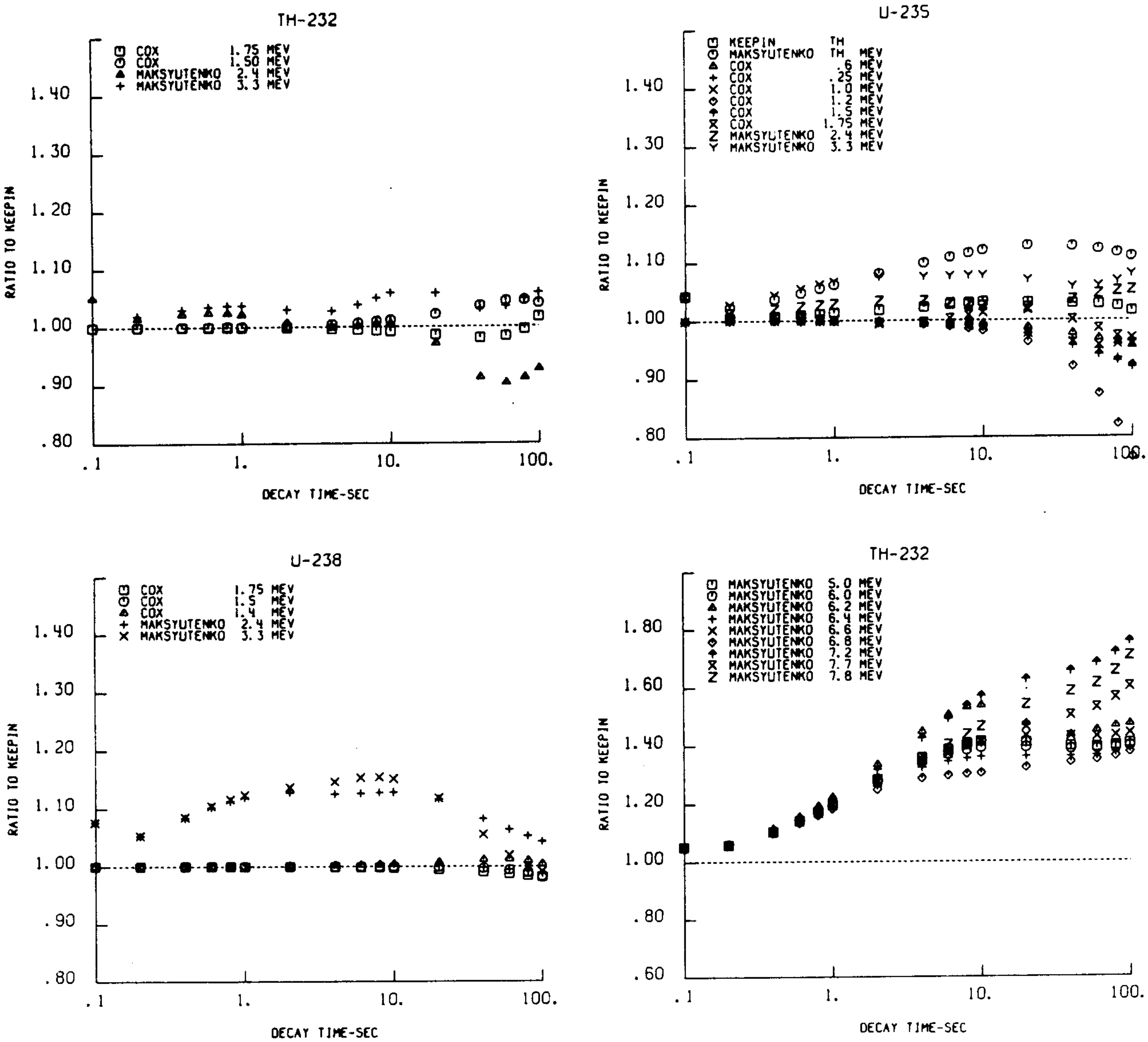

TH-232
COX 1.75 MEV
COX 1.50 MEV
MAKSYUTENKO 2.4 MEV
MAKSYUTENKO 3.3 MEV
RATIO TO KEEPIN
DECAY TIME-SEC
U-235
KEEPIN TH
MAKSYUTENKO TH MEV
COX .6 MEV
COX .25 MEV
COX 1.0 MEV
COX 1.2 MEV
COX 1.5 MEV
COX 1.75 MEV
MAKSYUTENKO 2.4 MEV
MAKSYUTENKO 3.3 MEV
U-238
COX 1.75 MEV
COX 1.5 MEV
COX 1.4 MEV
MAKSYUTENKO 2.4 MEV
MAKSYUTENKO 3.3 MEV
TH-232
MAKSYUTENKO 5.0 MEV
MAKSYUTENKO 6.0 MEV
MAKSYUTENKO 6.2 MEV
MAKSYUTENKO 6.4 MEV
MAKSYUTENKO 6.6 MEV
MAKSYUTENKO 6.8 MEV
MAKSYUTENKO 7.2 MEV
MAKSYUTENKO 7.7 MEV
MAKSYUTENKO 7.8 MEV

Fig. 12

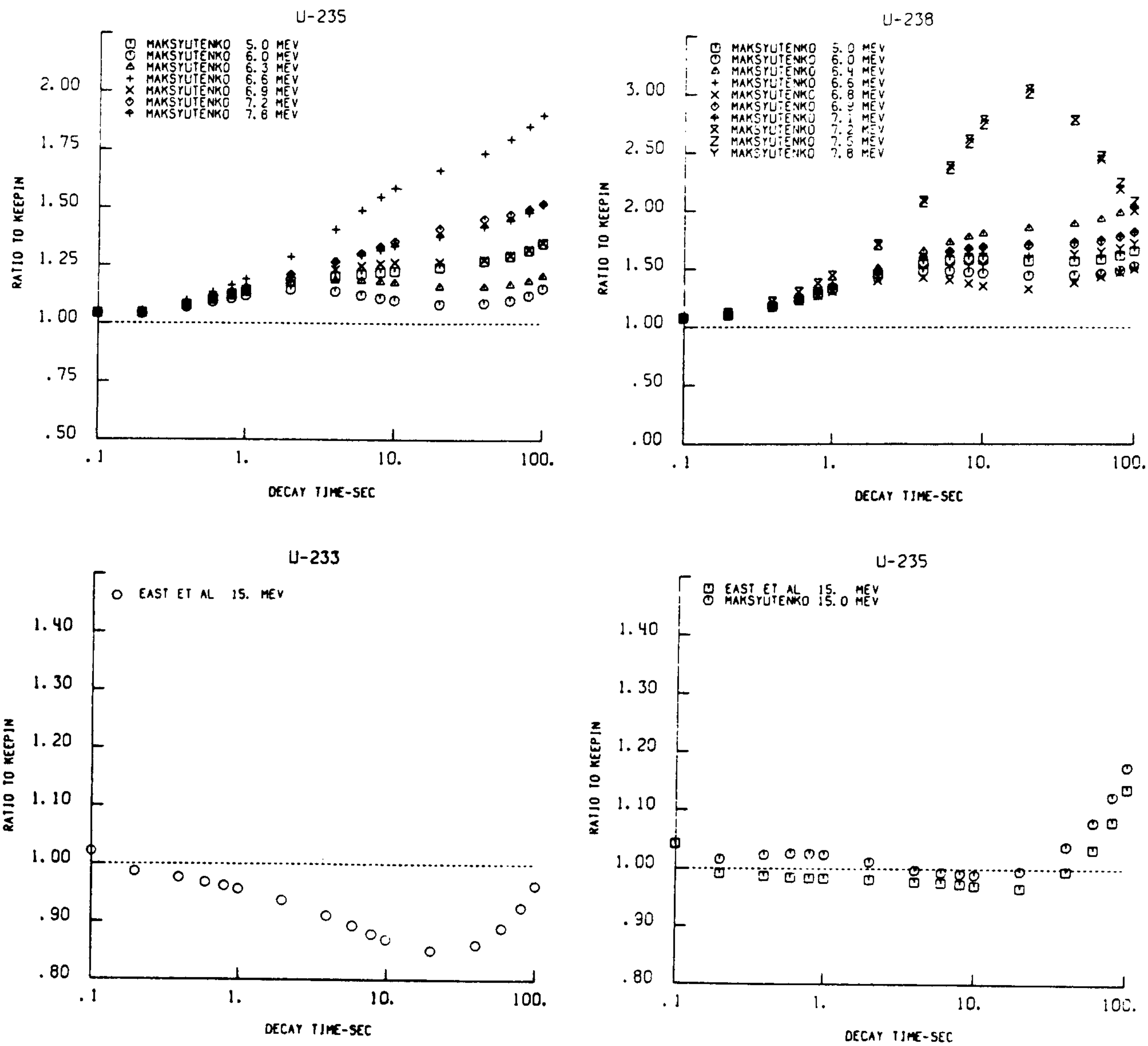

U-235
MAKSYUTENKO 5.0 MEV
MAKSYUTENKO 6.0 MEV
MAKSYUTENKO 6.3 MEV
MAKSYUTENKO 6.6 MEV
MAKSYUTENKO 6.9 MEV
MAKSYUTENKO 7.2 MEV
MAKSYUTENKO 7.6 MEV
RATIO TO KEEPIN
DECAY TIME-SEC
U-238
MAKSYUTENKO 5.0 MEV
MAKSYUTENKO 6.0 MEV
MAKSYUTENKO 6.6 MEV
MAKSYUTENKO 7.8 MEV
RATIO TO KEEPIN
DECAY TIME-SEC
U-233
EAST ET AL 15. MEV
RATIO TO KEEPIN
DECAY TIME-SEC
U-235
EAST ET AL 15. MEV
MAKSYUTENKO 15.0 MEV
RATIO TO KEEPIN
DECAY TIME-SEC

Fig. 13

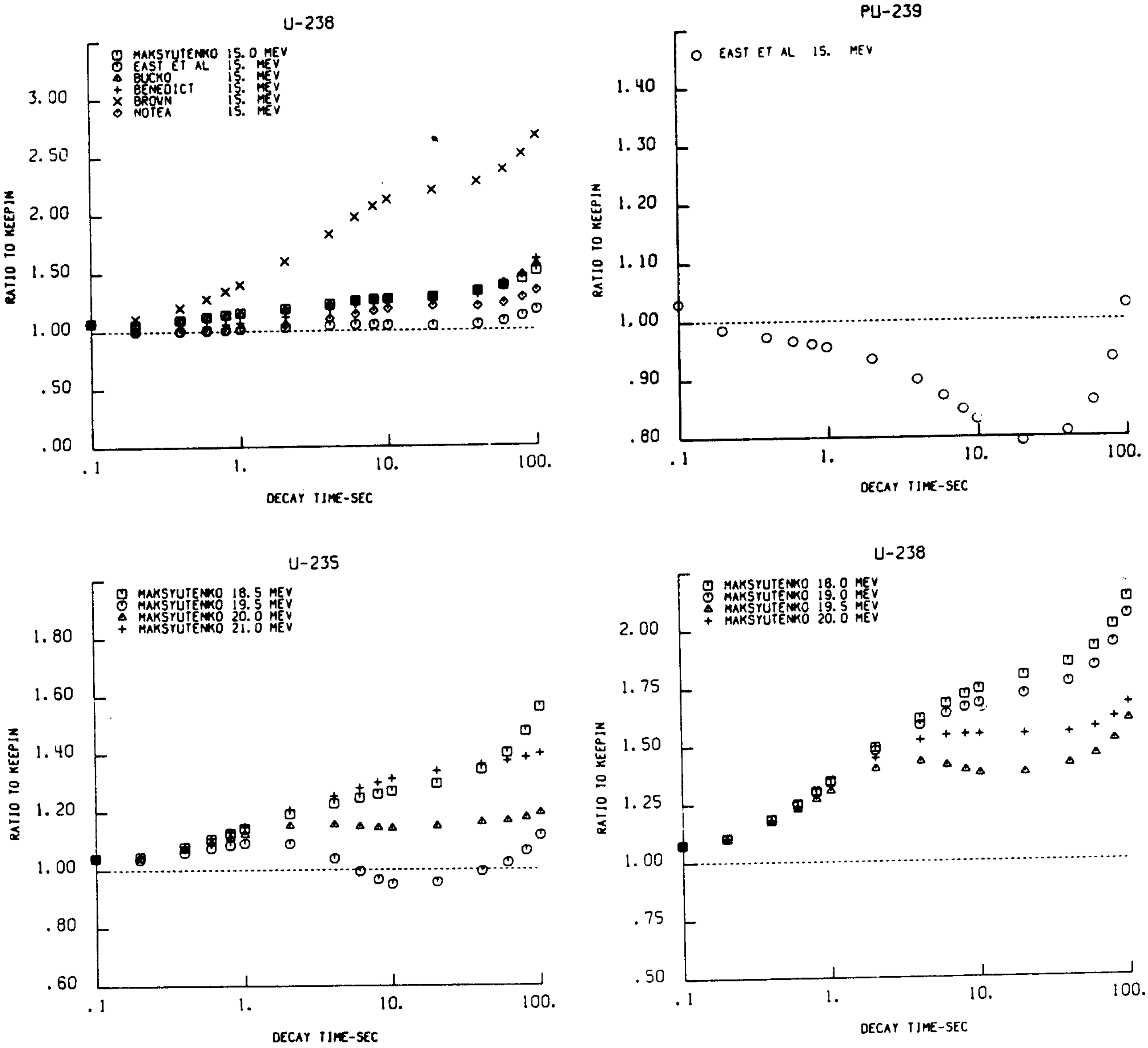

U-238
MAKSYUTENKO 15.0 MEV
EAST ET AL 15. MEV
BUCKO 15. MEV
BENEDICT 15. MEV
BROWN 15. MEV
NOTEA 15. MEV
RATIO TO KEEPIN
3.00
2.50
2.00
1.50
1.00
.50
.00
.1
1.
10.
100.
DECAY TIME-SEC
PU-239
EAST ET AL 15. MEV
RATIO TO KEEPIN
1.40
1.30
1.20
1.10
1.00
.90
.80
.1
1.
10.
100.
DECAY TIME-SEC
U-235
MAKSYUTENKO 18.5 MEV
MAKSYUTENKO 19.5 MEV
MAKSYUTENKO 20.0 MEV
MAKSYUTENKO 21.0 MEV
RATIO TO KEEPIN
1.80
1.60
1.40
1.20
1.00
.80
.60
.1
1.
10.
100.
DECAY TIME-SEC
U-238
MAKSYUTENKO 18.0 MEV
MAKSYUTENKO 19.0 MEV
MAKSYUTENKO 19.5 MEV
MAKSYUTENKO 20.0 MEV
RATIO TO KEEPIN
2.00
1.75
1.50
1.25
1.00
.75
.50
.1
1.
10.
100.
DECAY TIME-SEC

Fig. 14

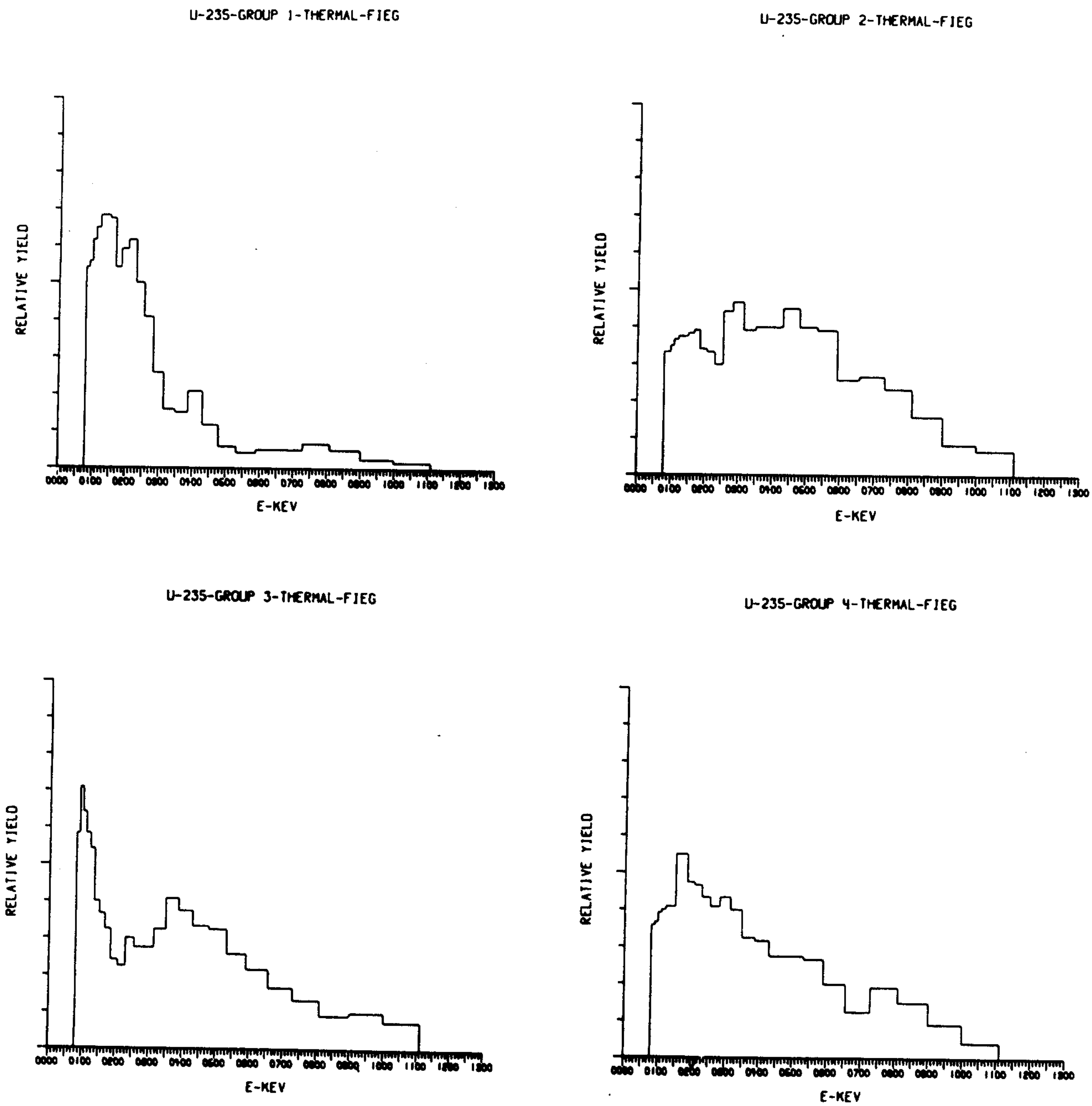
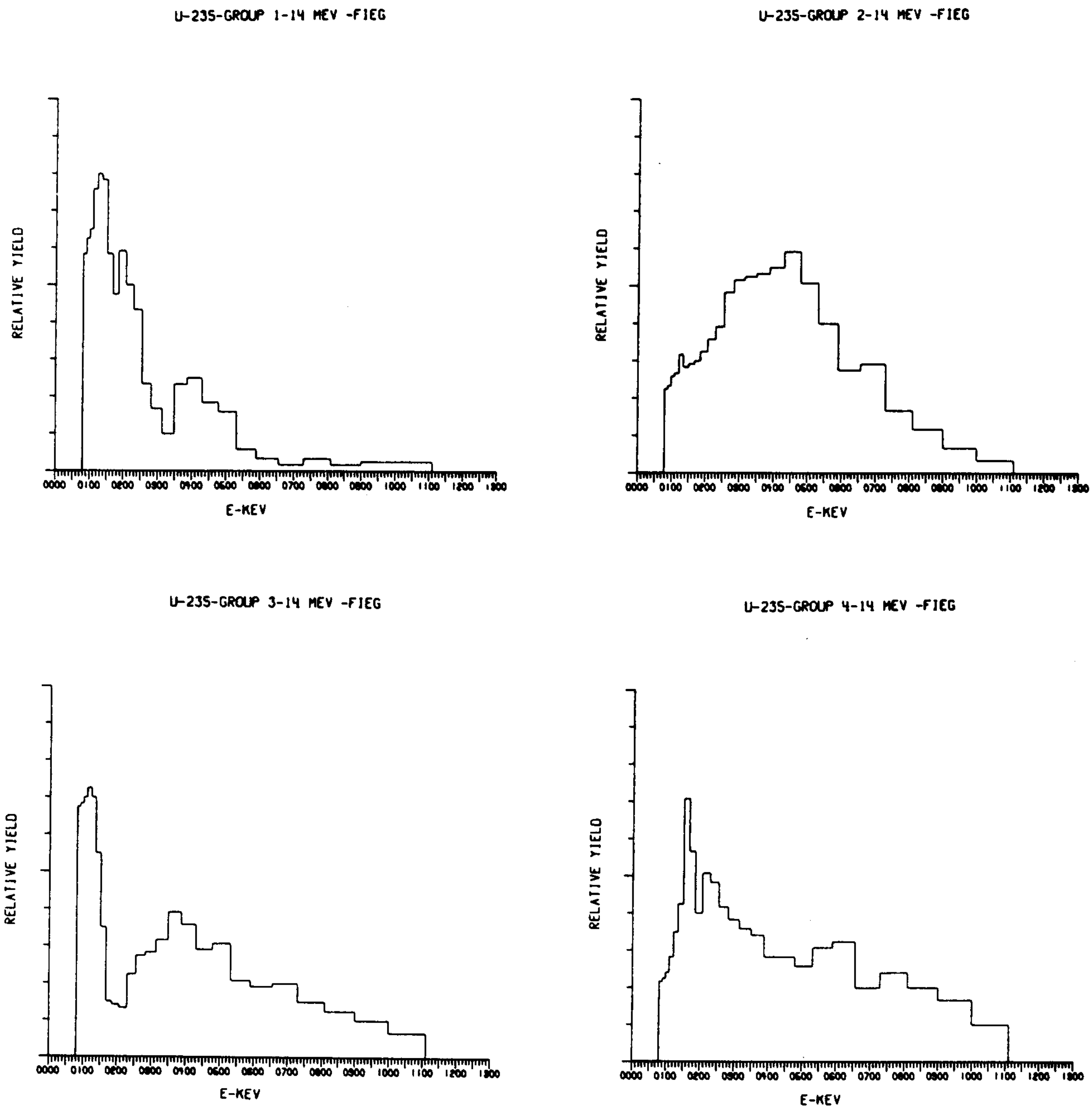
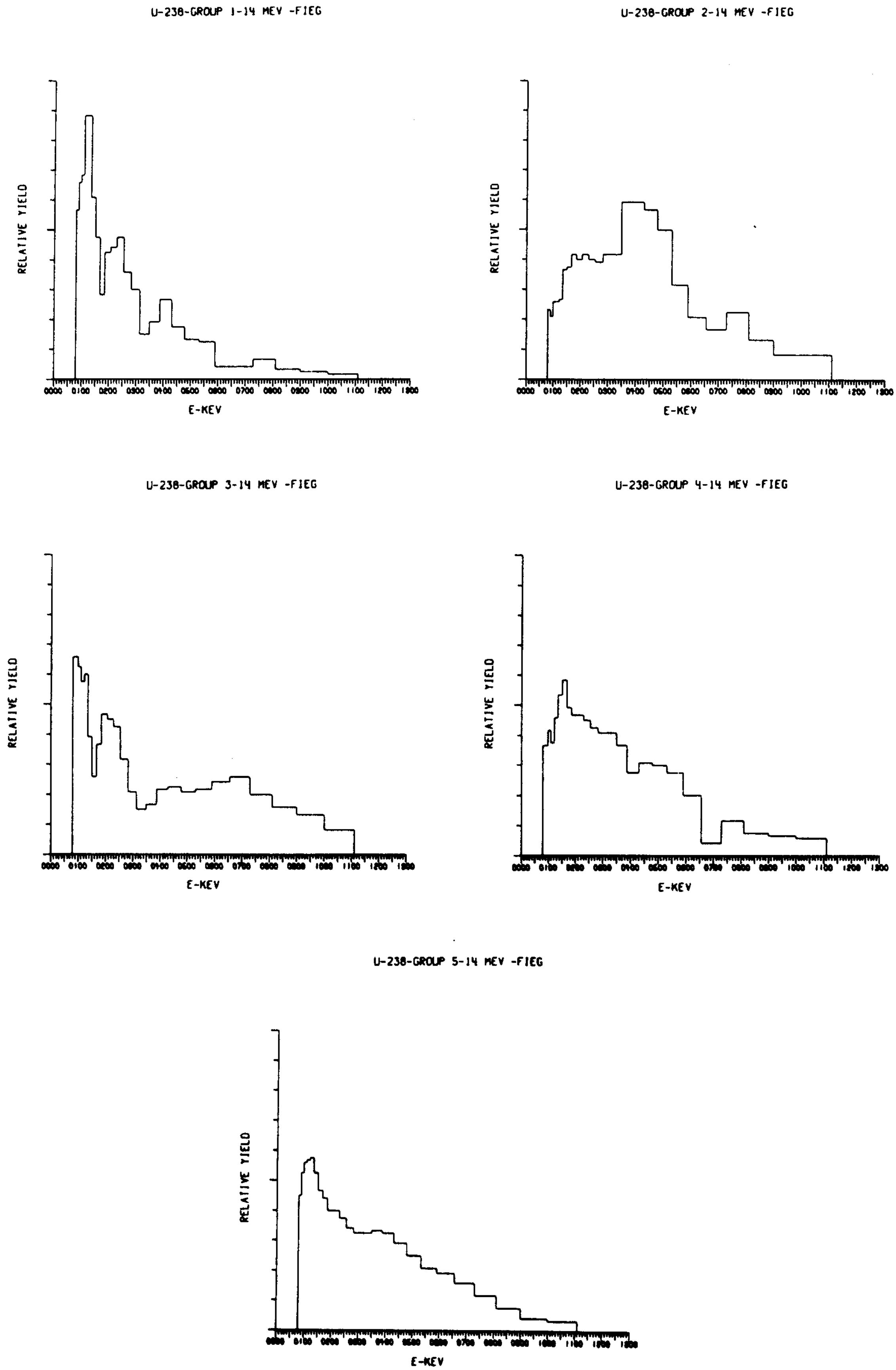

U-235-GROUP 1-THERMAL-FIEG
RELATIVE YIELD
E-KEV
U-235-GROUP 2-THERMAL-FIEG
RELATIVE YIELD
E-KEV
U-235-GROUP 3-THERMAL-FIEG
RELATIVE YIELD
E-KEV
U-235-GROUP 4-THERMAL-FIEG
RELATIVE YIELD
E-KEV

Fig. 15



U-235-GROUP 1-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-235-GROUP 2-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-235-GROUP 3-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-235-GROUP 4-14 MEV -FIEG
RELATIVE YIELD
E-KEV

Fig. 16



U-238-GROUP 1-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-238-GROUP 2-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-238-GROUP 3-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-238-GROUP 4-14 MEV -FIEG
RELATIVE YIELD
E-KEV
U-238-GROUP 5-14 MEV -FIEG
RELATIVE YIELD
E-KEV

Fig. 17

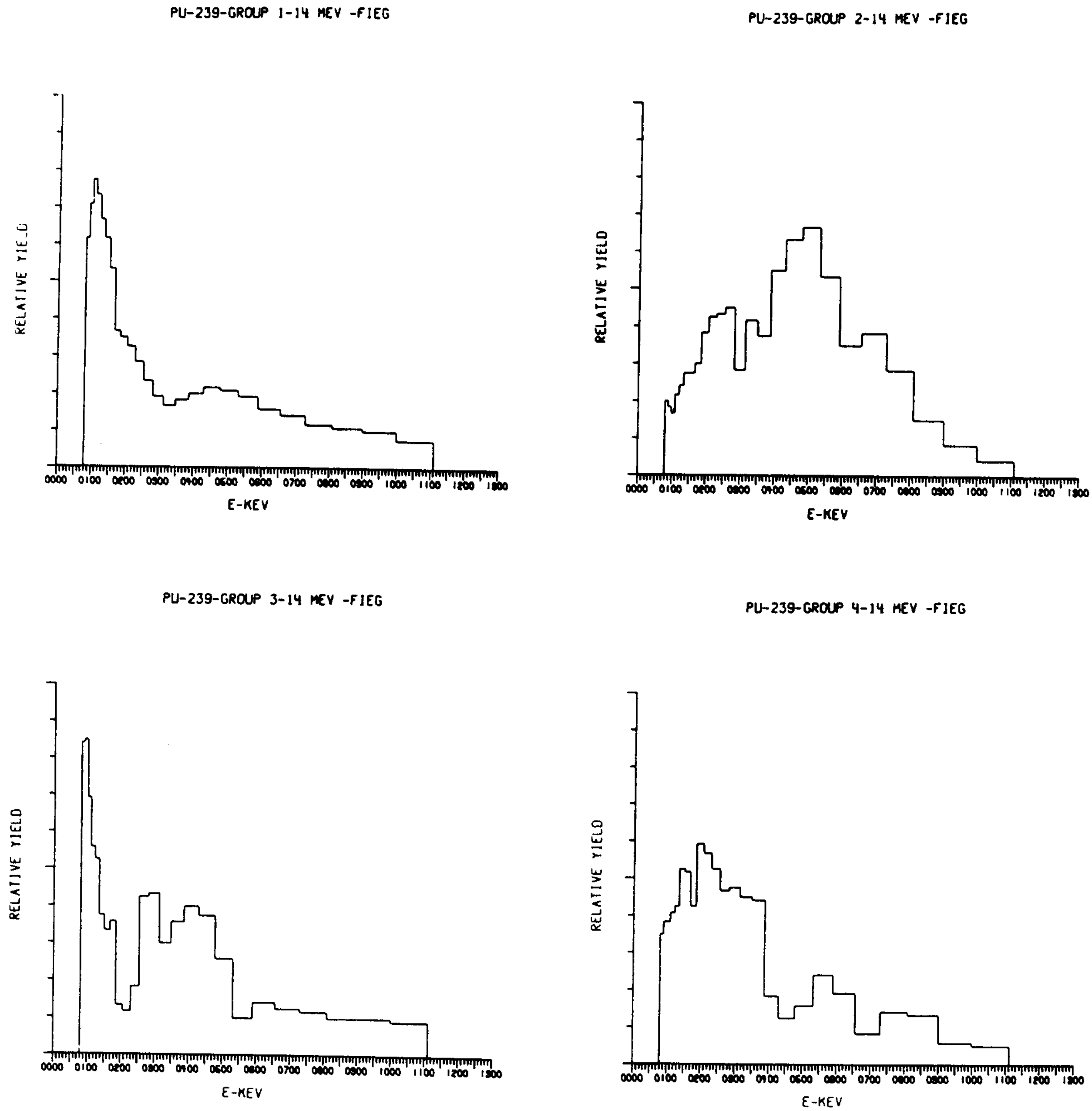
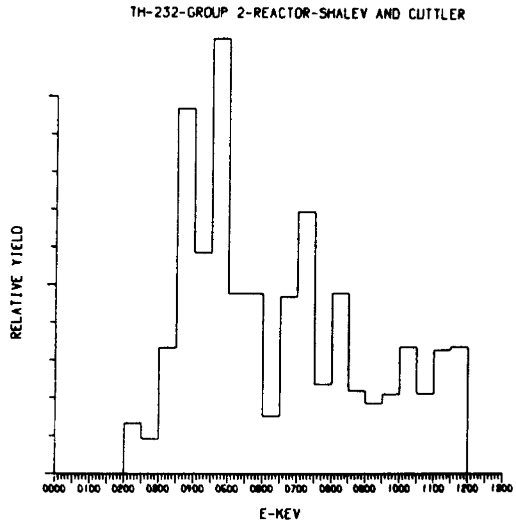
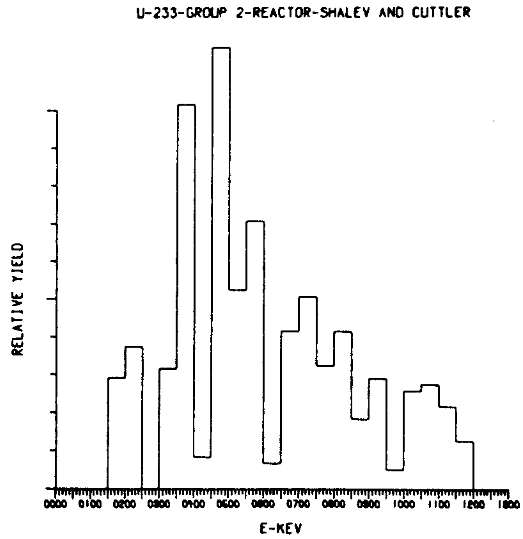

PU-239-GROUP 1-14 MEV -FIEG
RELATIVE YIELD
E-KEV
PU-239-GROUP 2-14 MEV -FIEG
RELATIVE YIELD
E-KEV
PU-239-GROUP 3-14 MEV -FIEG
RELATIVE YIELD
E-KEV
PU-239-GROUP 4-14 MEV -FIEG
RELATIVE YIELD
E-KEV

Fig. 18


TH-232-GROUP 2-REACTOR-SHALEV AND CUTTLER
RELATIVE YIELD
E-KEV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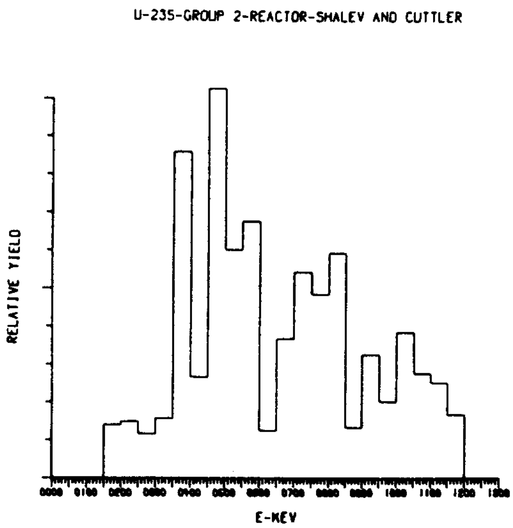
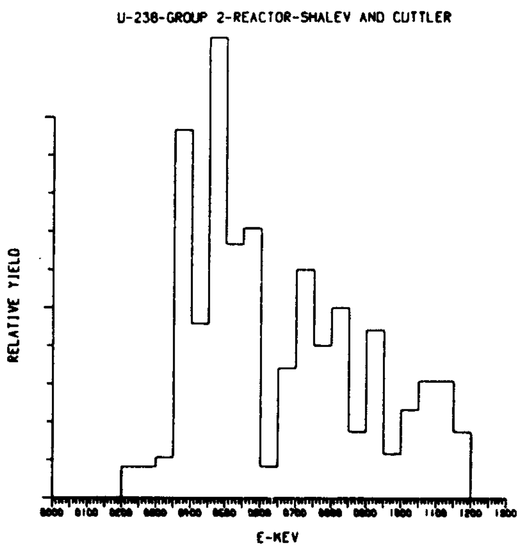
RELATIVE YIELD
E-KEV


U-235-GROUP 2-REACTOR-SHALEV AND CUTTLER
RELATIVE YIELD
E-KEV


U-238-GROUP 2-REACTOR-SHALEV AND CUTTLER
RELATIVE YIELD
E-KEV

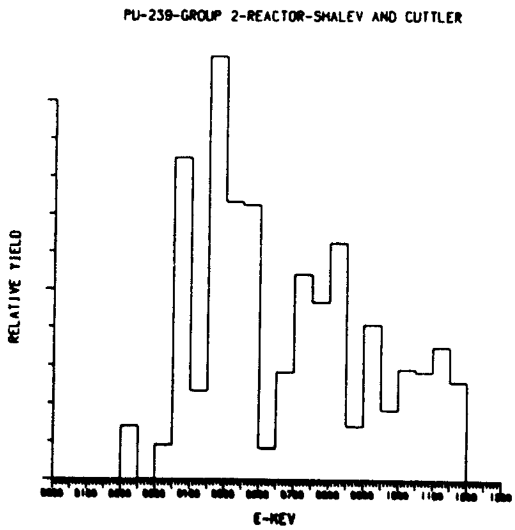

PU-239-GROUP 2-REACTOR-SHALEV AND CUTTLER
RELATIVE YIELD
E-KEV

TABLE I

Experimental Total Delayed Neutron Yields for ^{232}Th

Author	E_n-MeV	ν_d-n/f
Keepin 1957*	3.5	0.0505 ± 0.0020
Masters 1969	3.1	0.0570 ± 0.0040
Rose 1957**	3.0	0.0369 ± 0.0045
Keepin 1969	14.1	0.0315 ± 0.0037
Keepin 1969	14.9	0.0287 ± 0.0026
Masters 1969	14.9	0.0300 ± 0.0027
Herrmann 1966	14.0	0.0205 ± 0.0027
Notea 1969	14.0	0.0128 ± 0.0050
Benedict 1970	14.0	0.0191 ± 0.0065

*These data have been corrected for ν_d energy dependence.

**Rose data normalized to U^{235} using $\nu_d = 0.01668$.

TABLE II

Experimental Total Delayed Neutron Yields for ^{233}U

Author	E_n-MeV	ν_d-n/f
Keepin 1957	Thermal	0.0066 ± 0.0003
Conant 1970	Thermal	0.00671 ± 0.00041
Notea 1969	Thermal	0.00575 ± 0.00140
Rose 1957**	1.0	0.00716 ± 0.00043
Krick 1973	0.1-1.8	0.0075 ± 0.0006
Keepin 1957*	1.45	0.0073 ± 0.0004
Masters 1969	3.1	0.0074 ± 0.0008
Keepin 1969	14.1	0.00439 ± 0.00044
Keepin 1969	14.9	0.00433 ± 0.00044
Masters 1969	14.9	0.0041 ± 0.0003

*These data have been corrected for ν_d energy dependence.

**Rose data normalized to U^{235} using ν_d = 0.01668.

TABLE III

Experimental Total Delayed Neutron Yields for ^{235}U

Author	E_n-Mev	ν_d-n/f
Keepin 1957	Thermal	0.0158 ± 0.0007
Conant 1970	Thermal	0.0158 ± 0.0010
Clifford 1972	0.63	0.0174 ± 0.0008
Krick 1973	0.1-1.8	0.0163 ± 0.0013
Keepin 1957*	1.45	0.0167 ± 0.0007
Masters 1969	3.1	0.0172 ± 0.0013
Cox 1973	0.96	0.01650 ± 0.0010
Cox 1973	1.97	0.01657 ± 0.0010
Cox 1973	2.98	0.01696 ± 0.0010
Cox 1973	3.98	0.01666 ± 0.0010
Masters 1969	14.9	0.0091 ± 0.0004
Keepin 1969	14.1	0.0089 ± 0.0007
Keepin 1969	14.9	0.0088 ± 0.0007

*These data have been corrected for ν_d energy dependence.

TABLE IV

Experimental Total Delayed Neutron Yields for ^{238}U

Author	E_n-MeV	ν_d-n/f
Keepin 1957*	3.01	0.0421 ± 0.0025
Clifford 1972	2.77	0.0492 ± 0.0025
Masters 1969	3.1	0.0484 ± 0.0036
Rose 1957**	3.0	0.0367 ± 0.0025
Cox 1973	1.97	0.0439 ± 0.0026
Cox 1973	2.98	0.04347± 0.0026
Cox 1973	3.98	0.04288± 0.0026
Masters 1969	14.9	0.0283 ± 0.0013
Keepin 1969	14.1	0.0271 ± 0.0022
Keepin 1969	14.9	0.0255 ± 0.0021
Benedict 1972	14.8	0.0228 ± 0.0082
Notea 1969	14.0	0.0160 ± 0.0050

*These data have been corrected for ν_d energy dependence.

**Rose data normalized U^{235} using ν_d = 0.01668.

TABLE V

Experimental Total Delayed Neutron Yields for ^{239}Pu

Author	E_n-Mev	ν_d-n/f
Keepin 1957	Thermal	0.0061 ± 0.0007
Conant 1970	Thermal	0.0066 ± 0.0006
Notea 1969	Thermal	0.00517 ± 0.00200
Rose**	1.0	0.0068 ± 0.0004
Keepin*	1.58	0.0064 ± 0.0007
Krick 1973	0.1-1.8	0.0062 ± 0.0005
Masters	3.1	0.0066 ± 0.0005
Cox 1973	0.96	0.00674 ± 0.00043
Cox 1973	1.97	0.00669 ± 0.00043
Cox 1973	2.98	0.00640 ± 0.00043
Cox 1973	3.98	0.00663 ± 0.00043
Masters 1969	14.9	0.0041 ± 0.0002
Keepin 1969	14.1	0.00423 ± 0.00037
Keepin 1969	14.9	0.00451 ± 0.00041

*These data have been corrected for ν_d energy dependence.

**Rose data normalized to U^{235} using $\nu_d = 0.01668$.

TABLE VI

Experimental Total Delayed Neutron Yields for ^{240}Pu

Author	E_n-MeV	ν_d-n/f
Keepin 1957	2.13	0.0090 ± 0.0009
Keepin 1969	14.1	0.0063 ± 0.0009
Keepin 1969	14.9	0.0060 ± 0.0009

Experimental Total Delayed Neutron Yields for ^{241}Pu

Author	E_n-Mev	ν_d-n/f
Cox 1961*	Thermal	0.0157 ± 0.0015
Keepin 1969	14.1	0.00853 ± 0.00079
Keepin 1969	14.9	0.00814 ± 0.00074

*2% added to reported value to account for 6th group which was not measured.

TABLE VII

Data Recommended for ENDF/B-IV for ^{232}Th

$(E_n \leq 4.0$ MeV)

Total Yield: $\nu_d = 0.0527 \pm 0.0040$ n/f

Group	$T_{1/2}$ (sec.)	Relative Yield
1	56.030	0.034
2	20.750	0.150
3	5.740	0.155
4	2.160	0.446
5	0.571	0.172
6	0.211	0.043

Spectra:

Use Fieg Thermal U-235 data for groups 1, 3, 4. Substitute group 4 for groups 5, 6. Use Shalev data for group 2.

Transition Region (4.0-7.0 MeV)

Total Yield: Recommended representation is a linear connection between (E_n = 4.0 MeV, ν_d = 0.0527 n/f) and (E_n = 7.0 MeV, ν_d = 0.03 n/f).

Use same spectra and group yields as for $E_n \leq 4.0$ MeV.

(7.0-20.0 MeV)

Total Yield: $\nu_d = 0.03 \pm 0.0040$

Use same spectra and group yields as for $E_n \leq 4.0$ MeV.

TABLE VIII

Data Recommended for ENDF/B-IV for ^{233}U

($E_n \leq 4.5$ MeV)

Total Yield: $\nu_d = 0.0074 \pm 0.0004$

Group	$T_{1/2}$ (sec.)	Relative Yield
1	55.110	0.086
2	20.740	0.274
3	5.300	0.227
4	2.290	0.317
5	0.546	0.073
6	0.221	0.023

Spectra:

Use Fieg Thermal U-235 data for groups 1, 3, 4. Substitute group 4 data for groups 5, 6. Use Shalev data for group 2.

Transition Region (4.5-7.0 MeV)

Total Yield: Recommended representation is a linear connection between ($E_n = 4.5$ MeV, $\nu_d = 0.0074$ n/f) and ($E_n = 7.0$ MeV, $\nu_d = 0.0044$ n/f).

Use same spectra and group yields as for $E_n \leq 4.5$ MeV.

(7.0 - 20. MeV)

Total Yield: $\nu_d = 0.0044 \pm 0.00050$

Use same spectra and group yields as for $E_n \leq 4.5$ MeV.

TABLE IX

Data Recommended for ENDF/B-IV for ^{235}U

($E_n \leq 4.0$ MeV)

Total Yield: $\nu_d = 0.01668 \pm 0.00070$ n/f

Group	$T_{1/2}$ (sec.)	Relative Yield
1	54.51	0.038 ± 0.004
2	21.84	0.213 ± 0.007
3	6.00	0.188 ± 0.024
4	2.23	0.407 ± 0.010
5	0.496	0.128 ± 0.012
6	0.179	0.026 ± 0.004

Spectra:

Use Fieg Thermal neutron data for groups 1, 3, 4. Substitute group 4 for groups 5, 6. Use Shalev data for group 2.

Transition Region (4.0-7.0 MeV)

Total Yield: Recommended representation is a linear connection between (E_n = 4.0 MeV, ν_d = 0.0167 n/f) and (E_n = 7.0 MeV, ν_d = 0.0090 n/f).

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

(7.0 - 20.0 MeV)

Total Yield: $\nu_d = 0.0090 \pm 0.0010$ n/f

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

TABLE X

Data Recommended for ENDF/B-IV for ^{238}U

($E_n \leq 4.0$ MeV)

Total Yield: $\nu_d = 0.0460 \pm 0.0025$ n/f

Group	$T_{1/2}$ (sec.)	Relative Yield
1	52.38	0.013
2	21.58	0.137
3	5.00	0.162
4	1.93	0.388
5	0.493	0.225
6	0.172	0.075

Spectra:

Use Fieg 14 MeV data for groups 1, 3, 4, 5. Substitute group 5 for group 6. Use Shalev data for group 2.

Transition Region (4.0-8.0 MeV)

Total Yield: Recommended representation is a linear connection between (E_n = 4.0 MeV, ν_d = 0.046 n/f) and (E_n = 8.0 MeV, ν_d = 0.026 n/f).

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

(8.0-20.0 MeV)

Total Yield: $\nu_d = 0.026 \pm 0.0020$ n/f.

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

TABLE XI

Data Recommended for ENDF/B-IV for ^{239}Pu

($E_n \leq 4.0$ MeV)

Total Yield: 0.00645 ± 0.00040 n/f

Group	$T_{1/2}$ (sec.)	Relative Yield
1	53.75	0.038
2	22.29	0.280
3	5.19	0.216
4	2.09	0.328
5	0.549	0.103
6	0.216	0.035

Spectra:

Use Fieg 14 MeV data for groups 1, 3, 4. Substitute group 4 for groups 5, 6. Use Shalev data for group 2.

Transition Region (4.0-6.0 MeV)

Total Yield: Recommended representation is a linear connection between (E_n = 4.0 MeV, ν_d = 0.00645 n/f) and (E_n = 7.0 MeV, ν_d = 0.00430 n/f)

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

(7.0 - 20.0 MeV)

Total Yield: ν_d = 0.0043 ± 0.00030 n/f

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

TABLE XII

Data Recommended for ENDF/B-IV for ^{240}Pu

($E_n \leq 4.0$ MeV)

Total Yield: 0.0090 $\pm$ 0.0009 n/f

Group	$T_{1/2}$ (sec.)	Relative Yield
1	53.56	0.028
2	22.14	0.273
3	5.14	0.192
4	2.08	0.350
5	0.511	0.128
6	0.172	0.029

Spectra:

Use Fieg Pu-239 14 MeV data for groups 1, 3, 4. Substitute group 4 for groups 5, 6. Use Shalev Pu-239 data for group 2.

Transition Region (4.0-7.0 MeV)

Total Yield: Recommended representation is a linear connection between (E_n = 4.0 MeV, ν_d = 0.0090 n/f) and (E_n = 7.0 MeV, ν_d = 0.00615 n/f)

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

(7.0 - 20.0 MeV)

Total Yield: ν_d = 0.00615 $\pm$ 0.0006 n/f

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

TABLE XIII

Data Recommended for ENDF/B-IV for ^{241}Pu

($E_n \leq 4.0$ MeV)

Total Yield: 0.0157 ± 0.0015 n/f

Group	$T_{1/2}$ (sec.)	Relative Yield
1	54.0	0.010
2	23.2	0.229
3	5.6	0.173
4	1.97	0.390
5	0.43	0.182
6	0.2	0.016

(Group 6 estimated)

Spectra:

Use Fieg Pu-239, 14 MeV data for groups 1, 3, 4. Substitute group 4 for groups 5, 6. Use Shalev Pu-239 data for group 2.

Transition Region (4.0-7.0 MeV)

Total Yield: Recommended representation is a linear connection between (E_n = 4.0 MeV, ν_d = 0.0157 n/f) and (E_n = 7.0 MeV, ν_d = 0.0084 n/f)

Use same group yields and spectra as for $E_n \underline{\nu}$ 4.0 MeV.

(7.0-20.0 MeV)

Total Yield: $\nu_d = 0.0084 \pm 0.0006$ n/f

Use same group yields and spectra as for $E_n \leq 4.0$ MeV.

TABLE XIV

Delayed Neutron Energy Spectra for ^{235}U from Fieg[34], E_n = Thermal

EACH GRØUP IS NØRMALIZED TØ UNIT TØTAL YIELD

ENERGY(KEV)	GRØUP 1	GRØUP 2	GRØUP 3	GRØUP 4	GRØUP 5
79,73- 88,59	.0650	.0399	.0702	.0430	.0000
88,59- 98,43	.0668	.0402	.0852	.0442	.0000
98,43- 109,37	.0744	.0417	.0769	.0466	.0000
109,37- 121,52	.0783	.0439	.0695	.0481	.0000
121,52- 135,02	.0816	.0455	.0651	.0488	.0000
135,02- 150,02	.0820	.0453	.0484	.0495	.0000
150,02- 166,69	.0812	.0462	.0440	.0660	.0000
166,69- 185,22	.0648	.0468	.0385	.0657	.0000
185,22- 205,80	.0710	.0409	.0290	.0573	.0000
205,80- 228,66	.0741	.0398	.0271	.0558	.0000
228,66- 254,07	.0600	.0361	.0361	.0523	.0000
254,07- 282,30	.0492	.0532	.0334	.0495	.0000
282,30- 313,67	.0309	.0560	.0334	.0517	.0000
313,67- 348,52	.0191	.0471	.0387	.0476	.0000
348,52- 387,24	.0183	.0482	.0494	.0389	.0000
387,24- 430,27	.0251	.0479	.0448	.0384	.0000
430,27- 478,08	.0137	.0542	.0397	.0334	.0000
478,08- 531,20	.0066	.0485	.0385	.0328	.0000
531,20- 590,22	.0052	.0473	.0308	.0319	.0000
590,22- 655,80	.0057	.0309	.0261	.0236	.0000
655,80- 728,66	.0060	.0322	.0198	.0155	.0000
728,66- 809,63	.0079	.0280	.0155	.0227	.0000
809,63- 899,59	.0063	.0189	.0114	.0175	.0000
899,59- 999,54	.0034	.0098	.0116	.0107	.0000
999,54-1110,60	.0019	.0080	.0094	.0047	.0000
1110,60-1234,00	.0018	.0032	.0075	.0040	.0000

TABLE XV

Delayed Neutron Energy Spectra for ^{235}U from Fieg[34]; E_n = 14 MeV

EACH GRØUP IS NØRMALIZED TØ UNIT TØTAL YIELD

ENERGY(KEV)	GRØUP 1	GRØUP 2	GRØUP 3	GRØUP 4	GRØUP 5
79.73- 88.59	.0704	.0274	.0806	.0263	.0000
88.59- 98.43	.0747	.0283	.0825	.0273	.0000
98.43- 109.37	.0779	.0305	.0836	.0292	.0000
109.37- 121.52	.0910	.0320	.0868	.0338	.0000
121.52- 135.02	.0961	.0375	.0841	.0424	.0000
135.02- 150.02	.0944	.0341	.0662	.0508	.0000
150.02- 166.69	.0695	.0350	.0416	.0852	.0000
166.69- 185.22	.0566	.0362	.0185	.0675	.0000
185.22- 205.80	.0712	.0386	.0169	.0482	.0000
205.80- 228.66	.0601	.0429	.0161	.0605	.0000
228.66- 254.07	.0524	.0469	.0273	.0576	.0000
254.07- 282.30	.0278	.0577	.0328	.0498	.0000
282.30- 313.67	.0196	.0618	.0344	.0459	.0000
313.67- 348.52	.0115	.0626	.0382	.0431	.0000
348.52- 387.24	.0285	.0636	.0465	.0414	.0000
387.24- 430.27	.0304	.0661	.0434	.0338	.0000
430.27- 478.08	.0216	.0714	.0345	.0338	.0000
478.08- 531.20	.0189	.0614	.0371	.0311	.0000
531.20- 590.22	.0065	.0484	.0249	.0369	.0000
590.22- 655.80	.0041	.0333	.0226	.0393	.0000
655.80- 728.66	.0024	.0351	.0238	.0242	.0000
728.66- 809.63	.0036	.0202	.0177	.0292	.0000
809.63- 899.59	.0015	.0141	.0148	.0240	.0000
899.59- 999.54	.0029	.0079	.0117	.0197	.0000
999.54-1110.60	.0033	.0036	.0080	.0120	.0000
1110.60-1234.00	.0029	.0033	.0055	.0070	.0000

TABLE XVI

Delayed Neutron Energy Spectra for ^{238}U from Fieg[34]; E_n = 14 MeV

EACH GRØUP IS NØRMALIZED TØ UNIT TØTAL YIELD

ENERGY(KEV)	GRØUP 1	GRØUP 2	GRØUP 3	GRØUP 4	GRØUP 5
79,73- 88.59	.0679	.0284	.0793	.0435	.0543
88,59- 98,43	.0769	.0246	.0787	.0442	.0631
98,43- 109,37	.0822	.0310	.0751	.0503	.0673
109,37- 121,52	.1063	.0315	.0668	.0454	.0683
121,52- 135,02	.1059	.0322	.0718	.0550	.0688
135,02- 150.02	.0734	.0442	.0474	.0638	.0631
150,02- 166,69	.0571	.0448	.0312	.0701	.0564
166,69- 185.22	.0341	.0500	.0437	.0585	.0535
185,22- 205,80	.0505	.0481	.0563	.0560	.0480
205,80- 228.66	.0527	.0496	.0537	.0561	.0481
228,66- 254,07	.0569	.0481	.0513	.0537	.0450
254,07- 282,30	.0428	.0465	.0375	.0515	.0410
282,30- 313,67	.0356	.0500	.0249	.0487	.0392
313,67- 348,52	.0180	.0503	.0182	.0488	.0392
348,52- 387,24	.0231	.0712	.0200	.0440	.0399
387,24- 430,27	.0323	.0707	.0263	.0332	.0385
430,27- 478,08	.0209	.0682	.0269	.0366	.0351
478,08- 531,20	.0158	.0598	.0251	.0355	.0302
531,20- 590,22	.0154	.0385	.0263	.0328	.0254
590,22- 655,80	.0055	.0248	.0266	.0241	.0229
655,80- 728,66	.0048	.0201	.0311	.0054	.0188
728,66- 809,63	.0077	.0271	.0240	.0136	.0141
809,63- 899,59	.0044	.0159	.0188	.0095	.0088
899,59- 999,54	.0033	.0105	.0156	.0083	.0051
999,54-1110,60	.0024	.0096	.0101	.0075	.0040
1110,60-1234,00	.0022	.0042	.0093	.0041	.0019

TABLE XVII

Delayed Neutron Energy Spectra for ^{239}Pu from Fieg[34]; E_n = 14 MeV

EACH GRØUP IS NØRMALIZED TØ UNIT TØTAL YIELD

ENERGY(KEV)	GRØUP 1	GRØUP 2	GRØUP 3	GRØUP 4	GRØUP 5
79.73- 88.59	.0736	.0236	.1006	.0424	.0000
88.59- 98.43	.0853	.0221	.1023	.0456	.0000
98.43- 109.37	.0935	.0205	.0828	.0465	.0000
109.37- 121.52	.0881	.0257	.0672	.0485	.0000
121.52- 135.02	.0803	.0268	.0633	.0506	.0000
135.02- 150.02	.0741	.0330	.0455	.0630	.0000
150.02- 166.69	.0637	.0335	.0403	.0618	.0000
166.69- 185.22	.0443	.0364	.0425	.0512	.0000
185.22- 205.80	.0419	.0458	.0163	.0715	.0000
205.80- 228.66	.0386	.0508	.0141	.0680	.0000
228.66- 254.07	.0337	.0524	.0223	.0628	.0000
254.07- 282.30	.0279	.0537	.0505	.0556	.0000
282.30- 313.67	.0227	.0343	.0516	.0568	.0000
313.67- 348.52	.0203	.0504	.0364	.0538	.0000
348.52- 387.24	.0224	.0454	.0427	.0533	.0000
387.24- 430.27	.0244	.0660	.0475	.0224	.0000
430.27- 478.08	.0259	.0759	.0446	.0147	.0000
478.08- 531.20	.0251	.0798	.0314	.0193	.0000
531.20- 590.22	.0233	.0637	.0121	.0291	.0000
590.22- 655.80	.0186	.0419	.0171	.0225	.0000
655.80- 728.66	.0171	.0455	.0150	.0102	.0000
728.66- 809.63	.0136	.0343	.0137	.0174	.0000
809.63- 899.59	.0129	.0175	.0121	.0156	.0000
899.59- 999.54	.0121	.0100	.0121	.0072	.0000
999.54-1110.60	.0091	.0047	.0108	.0056	.0000
1110.60-1234.00	.0075	.0045	.0052	.0049	.0000

TABLE XVIII

Delayed Neutron Energy Spectra for Group 2 from Shalev and Cuttler[33]; E_n = reactor spectrum

EACH GRØUP IS NØRMALIZED TØ UNIT TØTAL YIELD

ENERGY(KEV)	TH-232	U-233	U-235	U-238	PU-239
	***********RELATIVE YIELD**********				
0. - 150.	(.039)	(.086)	(.058)	(.044)	(.063)
150. - 200.	.000	.035	.017	.000	.000
200. - 250.	.016	.045	.018	.010	.017
250. - 300.	.011	.000	.014	.010	.000
300. - 350.	.040	.038	.019	.013	.011
350. - 400.	.116	.122	.103	.116	.102
400. - 450.	.070	.010	.032	.055	.028
450. - 500.	.138	.140	.123	.145	.134
500. - 550.	.057	.063	.072	.080	.088
550. - 600.	.057	.085	.081	.085	.087
600. - 650.	.018	.008	.015	.010	.010
650. - 700.	.056	.050	.044	.041	.034
700. - 750.	.083	.061	.065	.072	.065
750. - 800.	.028	.039	.058	.048	.056
800. - 850.	.057	.050	.071	.060	.075
850. - 900.	.026	.022	.016	.021	.017
900. - 950.	.022	.035	.039	.053	.049
950. - 1000.	.025	.006	.024	.014	.022
1000. - 1050.	.040	.031	.046	.028	.035
1050. - 1100.	.025	.033	.033	.037	.034
1100. - 1150.	.039	.026	.030	.037	.042
1150. - 1200.	.040	.015	.020	.021	.031